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REVIEW

State-of-the-Art Gangue Entrainment Reduction Technologies in Mechanical Flotation Machines

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Abstract: Nowadays, the froth flotation process generally recovers low-grade and complex ores in large quantities. But it suffers from gangue entrainment of fine particles, to obtain high-grade concentrate products. To increase the recovery of valuable minerals, clayey, pyritic, and fibrous ores must be ground to a much smaller size, along with gangue minerals. These finely ground minerals not only affect sub-flotation processes in recovering valuable minerals based on true flotation, but also lead to high entrainment. In flotation, chemically unselective entrainment occurs simultaneously with true flotation. Entrainment occurs without a direct attachment of particles to bubbles. Gangue transport mechanisms and entrainment reduction techniques are serious challenges in mineral separation. This manuscript focuses on undesired gangue recovery mechanisms and their state-of-the-art prevention methods in mechanical flotation cells to increase metallurgical performance, froth stability, and mobility. Several operational, physical, and chemical methods have been developed and used on an industrial scale to decrease the impact of entrainment in the froth phase. The advantages and disadvantages of froth washing, pulp desliming, chemical reagent/binder clay/coarse particle addition, high-intensity conditioning, barrier usage, and ultrasonic pretreatment for gangue rejection in pulp and froth phases of mechanical flotation machines are highlighted in detail. Previous froth washing trials and applications at pilot and industrial scales are comprehensively reviewed to mitigate the entrainment problem in mechanical flotation machines.

Keywords: flotation, entrainment, slime coating, entrapment, froth washing, wash water

1 Introduction

Declining high-grade ores and rising demands for metals have increased dependence on processing low-grade ores in large quantities via froth flotation, which is one of the most popular mineral processing techniques [1]. These kinds of ores frequently have complicated mineralogy that needs to be finely ground in order to be sufficiently liberated. This leads to finer particles with less inertia, which adversely impacts hydrophilic gangue entrainment, a crucial component of froth flotation, as well as the bubble-hydrophobic particle attachment process. By lowering the concentrate's final grade, this restriction may eventually reduce the intended mineral recovery and increase the entrainment of fine gangue particles into the concentrate [2]. Both hydrophilic gangue and hydrophobic fine minerals are involved in entrainment. However, even a small amount of entrainment can drastically reduce the final concentrate grade because the fine gangue minerals are far more prevalent. Therefore, maintaining the quality of the final product and the metallurgical performance of the plant.

In the froth phase, hydrophobic valuable particles are strongly attached to the bubbles due to the presence of collectors, while gangue particles are in the inter-bubble water with weak or no attachment to the bubbles. Gangue transport in the froth is carried out through the inter-bubble water with fine gangue (-10 μm). The percentage of particles that enter the froth phase, endure its cleaning action, and are recovered as the concentrate in the launder is known as froth recovery [3]. The amount of saleable product in the concentrate, stated as a percentage of the overall concentrate, is known as the grade. Gangue entrainment, a non-selective process that transports fine particles from the pulp into the froth, lowers the grade of the concentrate. The liquid that is forced into the froth in the bubble wake or mechanical processes like turbulence and slime coatings entrain particles into the froth. Entrapment of fine gangue particles between bubbles/other particles and unattached particle transport upwards in the liquid around the bubbles (bubble lamella) are froth phase gangue transfer mechanisms [4].

One of the irreversible processes that takes place in all flotation froths is said to be froth drainage. Capillary suction produced by pressure differentials and gravity helps with this [5]. According to Szatkowski [6], the length and diameter of these capillaries, which are pathways between the mineralized bubbles, dictate how quickly gangue drains. Only the froth layers at the froth pulp interface can drain effectively. The deeper froths allow for additional drainage and reduce the wash water demand for froth washing. Overloaded bubbles in the froth, like in coal flotation, significantly decrease the drainage of water in the froth and create a stabilising effect. Well-drained froths require paddles for froth removal and, in turn, greatly increase the loss of recovery. Froth retention time plays a crucial role in both mineral recovery and froth drainage.

Numerous interrelated factors control the flotation process. True flotation and entrainment are the two ways that the solid particles go to the concentrate launder. The latter is directly tied to the water recovery in the concentrate, while the former depends on the particle's hydrophobicity. By adjusting the factors that influence water recovery, grades and/or recovery can be improved. Figure 1 shows the factors influencing gangue and water recoveries in the froth phase. Separation of true flotation and entrainment contributions facilitates a better evaluation of the process [4].

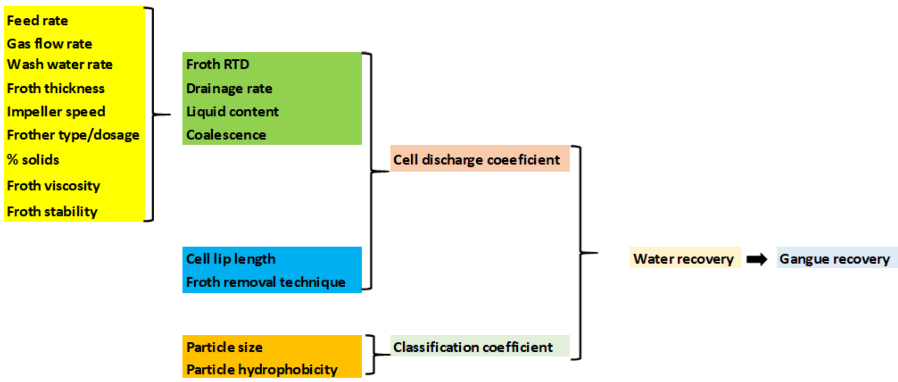


Figure 1 Summary of the factors influencing gangue and water recoveries in the froth phase [5]

A general relationship between entrainment and true flotation with particle size is first investigated by Trahar [7] and given in Figure 2. Hydrophobic valuable particle recovery is maximum in the particle size range of 10-100 μm (the top size may be system specific). At the fine end (-10μm), collision probability and efficiency with air bubbles are low, resulting in lower flotation kinetics and poor flotation recovery. At the coarse end (+100 μm), less effective particle suspension, a lower stability of coarse particle-bubble aggregates in the turbulent zone, a relatively slow and less complete surface coverage by collectors, and increased induction times decrease the recovery. Fine particle recovery can be increased either by increasing retention time or decreasing bubble size in the pulp phase, which both significantly increase gangue entrainment.

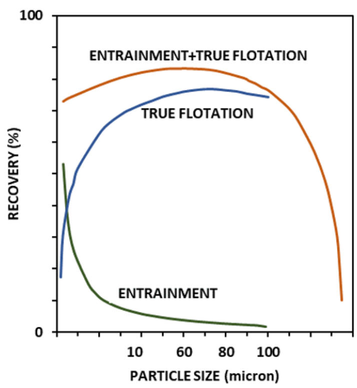


Figure 2 Effect of particle size on true flotation and entrainment [4]

Numerous investigations have been conducted to understand gangue recovery processes since entrainment negatively affects the grade and recovery of the flotation concentrate and prevents/minimizes it [4, 8–17].

Despite the critical importance of undesired gangue recovery and its state-of-the-art elimination technologies in mineral flotation separation, comprehensive reviews of recent research in this area have been scarce and insufficient. This manuscript concentrates exclusively on gangue recovery mechanisms and their mitigation technologies for mechanical flotation machines in two parts. The first part collects, reviews, discusses, and compares the findings from previous and recent studies on gangue entrainment mechanisms in conventional flotation systems. The second part investigates the previous entrainment reduction technologies and novel flotation cell designs, and seeks to explain some of the promising trends that emerged in the last four decades. Additionally, this study identifies knowledge gaps and offers recommendations for future research directions.

2 Valuable and gangue transport mechanisms

The turbulent zone and the quiescent zone are the two parts of the pulp phase in mechanical flotation cells. The impeller and stator uniformly distribute air into small bubble swarms in the perfectly mixed turbulence zone. These bubbles quickly collide with valuable minerals and absorb frothers. After that, they ascend to the quiescent zone, which is below the interface and above the turbulent zone, before becoming metastable. Particles begin the process of mass transfer to the froth phase when these bubbles arrive at the pulp-froth interface region.

Fully liberated valuable hydrophobic particles collide with air bubbles and form particle-bubble aggregates moving upwards against gravity to the froth in the pulp phase by chemical selective true flotation, while liberated hydrophilic coarse gangue particles report to the tailings. Valuable particles are also transported from the froth to the concentrate launder by horizontal movement through true flotation. Vertical transfer of some fine gangue and valuable particles from the pulp to the froth phase by entrainment and slime coating is unavoidable. In the froth phase, gangue particles move upward by entrapment or boundary layer entrainment while experiencing downward froth drainage of detached particles. In both mechanical cells and pneumatic flotation columns, fine hydrophilic gangue particles can report to the concentrate launder. There is a relationship between water and gangue recoveries in both conventional and pneumatic flotation cells.

In conventional flotation cells, two mechanisms (slime coating and entrainment) transfer fine particles from the pulp to the froth, as shown in Figure 3. Entrainment can be achieved in mechanical and hydraulic ways. Bubble wake mechanisms, also known as "hydraulic entrainment," involve particles being swept upward in the wake of rising bubbles. According to George et al. [18], a smaller bubble size has a lower related wake, which means that fewer gangue particles are entrained into the froth phase. Mechanical entrainment is caused by impeller motion, which causes turbulence and transfers fine hydrophilic particles to the slurry-froth interface. Bubble swarm rises, slows down, and accumulates at the interface. The buoyancy of the bubble swarm pushes some liquid with suspended particles above the interface due to limited drainage pathways [4, 11]. Mechanical entrainment is severe if the quiescent zone in the cell is absent or very low in depth, like in self-aerating and/or low-height/shallow mechanical flotation cells. In these cells, water recovery is high, and the impeller is not at the bottom of the cell. Bulk displacement of fine particles and water by internal radial and/or axial flow patterns may generate mechanical entrainment.

3 Overview of the froth behaviour

Transporting the precious hydrophobic minerals to the concentrate weir or froth discharge concentrate launders is the froth's primary function in flotation. To prevent bubble coalescence and bursting events during flotation, the froth must be sufficiently stable. Particle size and hydrophobicity, process water quality, bubble generation and dispersion mechanisms, particle contact angle, medium temperature, salt concentration, % solid, etc., influence the froth stability, which plays a significant role in determining concentrate grade and recovery.

To collect hydrophobic valuable minerals and drain fine hydrophilic gangue particles, the froth phase must be sufficiently stable. Because of its high mineral content, which stops hydrophobic particles from moving to the launder, an excessively stable froth is challenging to handle and causes problems with mineral recovery. Mineral-laden bubbles collapse before they are carried over the concentrate weir, which leads to low recovery if the froth is unstable (i.e., breaks constantly as the liquid drains from bubbles). Unstable froths are runny and consist of loosely packed spherical bubbles with little valuable minerals. A very stable froth is quite sticky, too viscous, too large in size, and heavily loaded with gangue minerals, which consequently

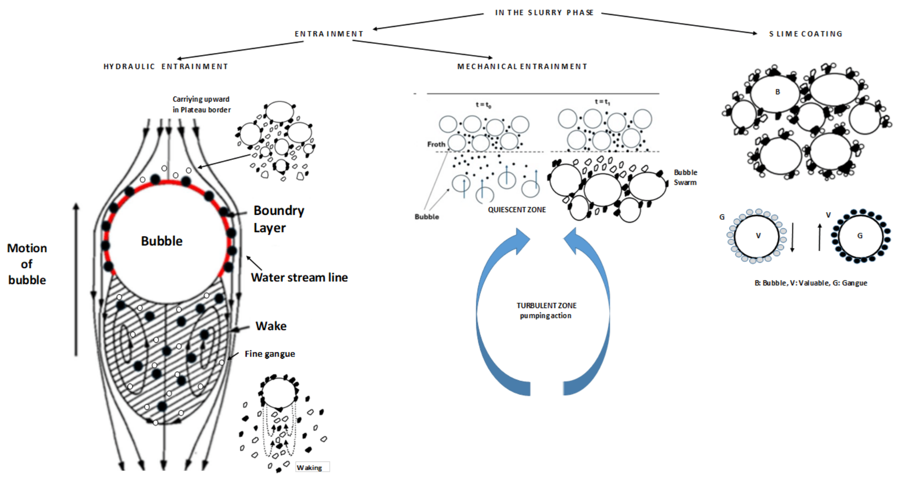


Figure 3 Gangue recovery mechanisms in the slurry phase [4]

leads to a poor grade of concentrate [19]. Stable froths become very dry in the top layers due to the drainage. Water spray may compensate for the water loss and prevent bubbles from bursting. Froth should also be mobile to freely flow from the pulp-froth interface to the overflow weir. Heavily loaded froths are stable, but they have high viscosity and low mobility to flow. Runny froth is too watery, low-mineralised, and excessively mobile. An ideal froth in flotation is not too viscous or too runny. Froth structure and rheology are important in flotation because of their effects on froth mobility and stability [20].

Sub-processes such as liquid drainage from Pleatau boundaries, particle detachment/attachment, and bubble coalescence and break-up determine the froth phase performance. Froth recovery and grade, which are commonly utilized as metallurgical performance indicators of the froth flotation, are designated by these sub-processes. The concentrate grade can be lowered by entrainment, entrapment, and slime coating processes, which are non-selective processes responsible for carrying fine gangue particles from the pulp into the froth phase. The pulp and froth phases of flotation have distinct gangue recovery processes. Gangue particles can be collected during the froth phase using hydraulic entrainment or entrapment. The thickness of the water layers that divide individual bubbles in a froth is known as liquid lamella thickness. Bubble coalescence happens when the liquid lamella thins and drains. The bubbles then enlarge and take on a polyhedral structure, with plateau borders, that is, tabular channels where water and detached particles flow downward, forming at the intersection of three bubbles. According to Jera and Bhondayi [21], detached particles can either sink and return to the pulp phase or reattach to the accessible surface of rising bubbles. Lamella thickness determines the carrying capacity of entrained particles, as well as the stability of the froth. Maximum gangue drainage occurs with the largest lamella thickness. Water can be dragged along the bubble walls, i.e., water is carried upwards in the bubble's hydrodynamic boundary layer (liquid lamella), which causes hydraulic entrainment in the froth phase and in the wake of an ascending bubble, causing hydraulic entrainment in the pulp phase. In the froth phase, entrainment occurs in the inter-bubble water by hydraulic entrainment and entrapment between bubbles (Figure 4). Hydraulically entrained fine gangue particles can be entrapped in the boundary layers if there is a blockage of the channels during water drainage [5].

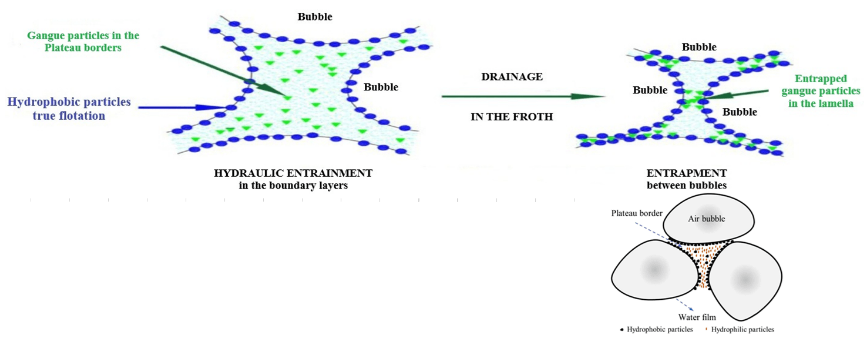


Figure 4 Gangue recovery mechanisms in the froth phase

4 Gangue recovery versus water recovery

Entrainment is strongly dependent on the water recovery, which carries the fine mineral particles into the concentrate in the flotation process [8, 22]. There is a parabolic relationship between water recovery and gangue recovery for coarse particles and a linear trend for ultrafine particles [11, 23]. Water recovery and gangue recovery curves for different size fractions tend to pass through the origin [15]. Gangue recovery by entrainment is directly proportional to water recovery only for ultrafine and narrow particle size range gangue [23]. Generally, the higher the water recovery, the higher the gangue recovery and the lower the concentrate grade [10, 17]. The degree of entrainment decreased with increasing particle size. Increasing the % solid, decreasing particle size of the feed, and increasing the aeration rate increase gangue recovery rates to the concentrate [10, 15, 16, 24, 25]. There is a hydraulic classification in the froth phase. The higher the froth thickness, the lower the water and gangue recoveries. The degree of entrainment is strongly dependent on size, with the coarser particles exhibiting a high degree of entrainment (ENT_i = 0) and the fine particles usually following the water phase (ENT_i = 1) [14]. It indicates that the coarser particles drain more easily from the lamella borders between the bubbles than fine gangue particles. Thus, coarse particles are hardly entrained in the concentrate.

The recovery of the gangue particles in the ith size fraction by entrainment ($R_{ent,i}$) can be calculated by Zheng et al. [15]:

$$R_{\text{ent,i}} = CF_i \cdot ENT_i \cdot R_w \quad (1)$$

where, CF_i: classification function; ENT_i: degree of entrainment; R_w: water recovery.

Zheng et al. [26] defined the CF_i. Two empirical models for the degree of entrainment were given by Bisshop and White [9] and Savassi et al. [14]. Maachar and Dobby [27] determined feed water recovery by tracer tests using potassium permanganate:

$$R_w = [c \cdot Q_c/(c \cdot Q_c + t \cdot Q_t)] \times 100\% \quad (2)$$

where, c and t are potassium permanganate tracer concentrations of the overflow and underflow, respectively, and Q_t volumetric tailing and Q_c concentrate flow rates, respectively.

Other empirical models, like Kirjavainen's [28], try to include other factors, including slurry viscosity and particle morphology. These factors are challenging to quantify in plant practice, though.

Increasing the impeller speed increases the collision probability in the pulp phase and fully disperses solids in the cell. But it can also increase the mechanical entrainment in the pulp phase and may disturb froth stability. Akdemir and Sönmez [29] and Çilek [25] reported increased entrainment as a result of increased impeller speeds. Used impeller and stator types change the hydrodynamics of the flotation cell and are also important for entrainment [30, 31]. Maachar and Dobby [27] reported that entrainment of hydrophilic fine silica (< 5 μm; SG 2.6 g/cm^3) was higher than galena (< 5 μm; SG 7.5 g/cm^3) in laboratory column flotation tests. But the effect was small. Increasing the air flow rate increases the degree of entrainment of a particular size for a given froth thickness. Increasing the air flow rate leads to bigger and faster-moving bubbles with more water recovery. Froth stability and drainage can change with air flow rate variations.

Froth height significantly affects the gangue entrainment. The higher the froth thickness, the fewer gangue particles are entrained into the concentrate. Shallower froths are wetter than deeper froths. Wetter froths transport more gangue to the concentrate. Less gangue is transported to the concentrate in deep froths because of the increased froth retention time, and promotes higher drainage changes [6].

Average froth retention time includes the vertical and horizontal movement times for the bubbles. Vertical froth retention time is directly related to the froth height and indirectly related to the superficial air flow rate. Gangue recovery can be decreased by increasing froth thickness and/or by decreasing air flow rate. The higher the froth retention times provide the longer the time for froth drainage.

Trahar and Warren [32] determined the relationship between water recovery and solids recovery with and without a collector in the presence of frother addition (Figure 5). Without the collector addition, the recovery was due to the entrainment. Hydrophilic particles were recovered by water. With the collector and frother addition, the solids recovery was due to both true flotation and entrainment. Hydrophobic particles are mainly recovered by true flotation. The difference between the solids recovered versus water recovered, for collector and no collector addition tests, showed the estimate of the mass recovered by true flotation [33].

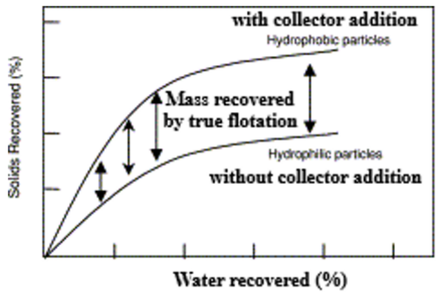


Figure 5 True flotation and entrainment determination by the Trahar and Warman [32] method

Creux [34] showed that silica was not recovered by entrainment alone without the cationic collector addition due to the negative charge of both bubbles and fine silica. Warren [35] proposed the equation:

$$R(t) = F + eW(t) \tag{3}$$

where R(t) is the mineral recovery and W(t) is the water recovery as a function of time, t. F is the recovery due to the true flotation, and e is the degree of entrainment, which is equal to the slope of the R(t) versus W(t) plot. A series of solid recovery experiments is performed by changing froth depth and froth removal rate. A regression line between total solids recovered and water recovery can be obtained. Zero water recovery extrapolation in the graph gives the true flotation, and the slope of the line gives the degree of entrainment [18].

Ross and Van Deventer [36] estimated the flotation rate:

$$R(t) = F + R_e(t) \tag{4}$$

$$F = R(t) - W(t)(C - bt) \tag{5}$$

$$R_e(t) = W(t)(C - bt) \tag{6}$$

where R(t) is the overall recovery by true flotation and entrainment, F is the true flotation, R_e(t) is the recovery by entrainment, W(t) is the water recovery, and C initial concentration of the mineral species in the pulp. b is the slope of mineral concentration remaining in the pulp phase versus time (t).

George et al. [18] introduced a new hydrophobic (hydrophobised silica (40-150 nm in diameter and 1% suspension) with CTAB cationic collector) - hydrophilic (alumina (d_{50}: 150 nm) particle technique in the presence of frother and collector for assessment of true flotation and entrainment. Comparison of Trahar and Warren [32], Warren [35], and Ross and Van Deventer [36] techniques with the George et al. [18] technique showed highly consistent results for 6 cm froth thickness. True flotation changed between 79% to 86%.

5 Gangue recovery mechanisms

5.1 Entrainment

The main process for recovering completely liberated and dispersed fine gangue particles (-10 μm) is entrainment. For particles coarser than around 50 μm, entrainment is typically negligible. The process by which small particles move up and out of the flotation cell suspended in the water between bubbles after entering the base of a flotation froth is known as entrainment. It is important to distinguish between entrainment and "true flotation," in which particles exit the cell adhered to bubble surfaces. Entrainment can recover both precious minerals and fine gangue, in contrast to chemically selective true flotation. However, as the recovery of the more prevalent gangue mineral lowers the quality of the final concentrate, entrainment is typically seen as detrimental to the ultimate product grade. The processing of fine ores has been particularly affected by this [11]. Entrainment starts in the pulp phase, crosses the pulp-froth interface, and enters the froth phase by two mechanisms named hydraulic and mechanical entrainment. Hydraulic entrainment carries unattached fine particles upward either in bubble lamella (surface entrainment) or in the bubble wakes (dragged behind). Mechanical entrainment is caused by the pomping power of the impeller. Flow patterns push the bubble swarm upwards. In shallow coal flotation cells, the impeller is not at the bottom, and air is sucked from the atmosphere. In this cell design, the quiescent zone above the turbulent zone is not deep enough to prevent fine gangue particles from escaping into the froth phase. Feed properties (particle size and mineralogy, and density), and operational parameters (pulp density, mixing speed, air flow rate, and froth height) have a significant influence on entrainment [4, 21, 37].

In saline flotation water, entrainment rises. By preventing bubble coalescence and boosting water recovery, which encourages gangue entrainment, inorganic salts improve froth stability. Salts increase bubble-particle and particle-particle attachment by disrupting hydration layers and compressing the electrical double layer (EDL) repulsions between particles and bubbles [38].

Much flotation research has focused on reducing entrainment to improve the final product grade. This was one of the reasons behind the development of the column flotation between 1980 and 1990, the Jameson cell between 1990 and 2000, other pneumatic flotation cell systems between 2000 and today, and the Eriez-StackCell mechanical machine between 2017 and today.

In the froth phase of mechanical flotation cells, gangue rejection is primarily accomplished by mechanical, hydraulic, or geometrical techniques. Geometrically, froth thickness increase and flow modifier use increase the mean retention time in the froth phase. Mechanically, the use of rod barriers (like Wemco-Leeds Flotation machines) [39] and froth vibration (mechanical/ultrasonic) increases coalescence and strips gangue by bubble deacceleration [40, 41]. Hydraulically, froth washing in mechanical or pneumatic cells/columns decreases froth retention time, increases drainage, and decreases coalescence. Table 1 summarises the principle factors affecting entrainment in flotation.

Table 1 Principle factors affecting entrainment in flotation [4, 42, 43]

Increasing in	Entrainment increases	Entrainment decreases	Reference(s)
water recovery	+		[5], [8], [10], [11], [15], [17], [22], [23], [44]
pulp percent solid	+		[8], [10], [15], [16], [24], [25], [35]
particle size		+ (settling rate increases)	[7], [11], [14], [15], [31], [45], [46], [47], [48], [49], [50]
particle specific density		+ (settling rate increases)	[11], [27], [44], [48], [51], [52]
impeller speed	+ (Decreases both pulp and froth retention times with small bubbles)		[25], [29], [30], [31], [50]
air flow rate	+ (Bubble/froth rising velocity increases, froth retention time decreases, and froth drainage rate decreases)		[4], [9], [15], [31], [50]
froth height		+ (Prolongs the froth retention time, increases the froth drainage rate)	[4], [6], [15], [23], [50], [53], [54]
froth retention time		+ (drainage rate increases)	[5], [6], [15]
froth mobility and stability (by wash water addition)		+	[55]

Traditional industrial practice for mitigating the entrainment problem was the use of multi-stage cleaner flotation cells [56]. Instead of expensive and time-consuming multi-stage cleaner usage, some common operating solutions in the flotation industry were developed in the last decades to alleviate the entrainment problem [4, 12, 21, 40]:

(1) The use of deeper froth thickness and/or lower aeration rates (i.e., increasing retention time in the froth phase) to decrease water recovery to the concentrate (N. American practice): Changing froth depth alters the mean froth retention time. Changing the froth retention time alters froth and water recoveries and froth drainage. Adding weir bars maintains pulp level (which keeps the same cell volume and therefore retention time) and increases froth depth, which increases froth drainage back into the pulp phase. Changing the air flow rate also alters water recovery across the froth. Decreasing the air flow rate leads to a decrease in froth rising velocity and entrainment with increasing average froth retention time [4]. Deep froths promote selectivity in flotation due to increased coalescence. Coalescence causes the particles to detach as well as reattach to bubbles.

(2) The use of froth-flow modifiers near the concentrate weir, such as baffles/diverters, crowders, inner/peripheral launders, or paddles, also changes the froth retention time and impacts

entrainment recovery. Increasing froth retention time with an elongated bubble path, increasing drainage rate, reducing dead zones, improving froth flow, and removal dynamics. The use of PVC rod barriers, like in Wemco-Leeds cells, was suggested by Degner and Person [57]. Inserting froth modifiers altered froth retention time and allowed more drainage (S. African practice) [37, 53, 58].

(3) Entrainment is traditionally minimised using multi-stage cleaner flotation to dilute the concentration of the impurities in the flotation feed. Dilution of the pulp phase by adding water into the concentrate launders or conditioning tanks (Australian practice) [4]. Multistage cleaning with diluted pulps was not practicable in coal flotation due to the large capital costs in N. America [59].

(4) Reducing turbulence in the pulp creates a quiescent zone between the turbulent zone and the froth zone. Impeller speed reduction and horizontal baffle usage create a quiescent zone, thereby reducing the probability of mechanical entrainment [25, 37, 53, 60, 61]. Although baffles were beneficial, the operational challenges exceeded the advantages [53].

(5) Froth vibration was used to stimulate gangue drainage [12, 43]. Ultrasonic vibration both encouraged the coalescence and slowed the froth phase [40]. Froth vibration aided drainage at the expense of recovery.

Froth washing increases froth mobility and stability, decreases coalescence, and washes out gangue particles to the froth phase [4, 12, 62, 63]. Froth washing in mechanical cells is a significant alternative to multi-stage cleaning circuits for conventional mechanical flotation cells. Froth washing creates a net downward flow of water, which washes gangue [59, 64–67]. Slime coating is another mechanism for transporting gangue into the froth [4, 12].

5.2 Slime coating

The slime coating is a probable source of gangue transfer from the slurry phase to the froth phase. In froth flotation, it is a major undesirable phenomenon. Slime coating, which covers a valuable coarse mineral with gangue slimes to keep it from coming into direct contact with collectors and/or air bubbles, has long been recognized to have negative effects.

As ore grades decline and mineral dispersal becomes more complicated, ores must be finely crushed to liberate important minerals for extraction. Large amounts of fine gangue minerals (-10 μm) are created during the size reduction process because of the ore's clay concentration or fine grind. The most popular mineral separation method now in use, froth flotation, is negatively impacted by these tiny gangue mineral particles, often known as "slimes." The slimes are entrained into the froth product and raise pulp viscosity and reagent consumption. Slime coating happens in sulphide, oxide, and salt types of minerals, and coal and bitumen flotation. Initially, researchers attributed slime coatings to electrostatic attraction between gangue and valuable coarse particles [68, 69]. But later, it was found that the same sign of charge gangue slimes also coats the valuable mineral surface [70, 71]. From a chemical perspective, it was discovered that the two main mechanisms supporting slime coatings are the classical Derjaguin–Landau–Verwey–Overbeek (DLVO) theory and the expanded DLVO theory. The aggregation and dispersion of colloidal particles and slime coatings on coal and clay particles have been extensively explained by the classical DLVO theory, which relies on weak van der Waals forces and electrostatic interactions [72]. According to Yao et al. [71, 73], the expanded DLVO theory provides a better explanation for the interaction behaviours of quartz (SiO_2), dolomite ($CaMg(CO_3)_2$), and magnesite ($MgCO_3$) than the standard DLVO theory.

Another cause of slime coating is the deposition of hydrophilic colloidal molecules created during grinding on desirable coarse particles. Sphalerite (ZnS) can be significantly oxidised during dry grinding, forms smithsonite ($ZnCO_3$) slime coating on the surface, and is depressed by the ZnS [74]. Also, during grinding, galena (PbS) surfaces can be coated by colloidal iron oxide/ hydroxides coming from grinding media, and the flotation performance of PbS decreases [75]. Colloidal particles that occur during grinding can be attracted to the coarse particle surfaces because of the compaction or impact during comminution.

Chemical precipitation is an additional suggested cause of slime coating and is intricately linked to the chemistry of the pulp solution. Ca-ions dissolved from gypsum ($CaSO_4 \cdot 2H_2O$) react with sodium carbonate (Na_2CO_3), form $CaCO_3$, which coats the surface of coarse valuable mineral, and affects coal flotation [76]. Wang et al. [77] found that hydrophilic precipitates have a significant adverse effect on coal flotation.

The slimes might come from gangue minerals and valuable-gangue composite particles, or they can come from colloidal compounds created during mineral processing as a result of chemical precipitation, excessive grinding, and oxidation of the mineral surface [78]. From a better metallurgical performance point of view, control and prevention of slime coating in froth flotation is critical.

Scanning electron microscopy (SEM) in conjunction with energy-dispersive X-ray spectroscopy (EDS), electrokinetic measurements, induction time measurements, atomic force microscopy (AFM) interaction force measurements, and the quartz crystal microbalance with dissipation technique (QCM-D) can all be used to identify and measure slime coating. Details, benefits, and drawbacks of the aforementioned methods for a straightforward static binary mineral/coal-clay system are provided by Yu et al. [78].

5.3 Factors influencing slime coatings

Solution chemistry, mechanical energy input, surface oxidation, and properties of the slimes are principal factors affecting slime coatings in flotation.

5.3.1 Solution chemistry

Slurry pH and the addition of electrolyte change the solution chemistry significantly. pH is the negative logarithm of the hydrogen ion (H^+) concentration and is defined as a measure of the acidity or basicity of a solution. The two most significant counter-ions of the mineral surface, H^+ and hydroxide ions (OH^-), are regulated by pulp pH. The pulp's pH can be altered to alter the mineral surface charges. Minerals are positively charged when the pH of the solution is below the isoelectric point (IEP) and negatively charged when the pH is above IEP. The absolute value of zeta potential steadily rises as pH departs from IEP [79]. As a result, altering the pH of the flotation pulp may cause the zeta potential of the mineral surface to shift. This will alter the electrostatic force between the hydrophilic clay gangue particles and the hydrophobic coarse mineral particles, which will impact the particles' dispersion and aggregation [80]. If the signs of the zeta potential of hydrophobic mineral and clay gangue surfaces are opposite at the same pulp pH, there will be an attractive electrostatic force. Coupled with the attractive van der Waals forces, the clay gangue and hydrophobic mineral attract each other to form slime coatings. In contrast, the two particles can repel each other if they carry the same charge signs, offsetting the van der Waals force and causing dispersion.

Bandini et al. [75] studied the effect of pH on the adsorption of iron oxide slimes (25-38 μm) on PbS particles. They found that slime adsorption/attachment on PbS increased with increasing slime concentration and decreasing pulp pH. The IEP of iron oxide was 8.4. Several IEPs have been reported by PbS. Kelebek and Smith [81] and Vergoum et al. [82] suggested the IEP of PbS around 2.4. Between pH 4 and 8, significant slime coatings occurred. At pH: 10, iron oxide has the same sign charge as PbS, and the slime coating was very low.

The electrostatic interactions between hydrophobic mineral and clay gangue particles are altered by the addition of electrolyte, which also modifies the zeta potential's amplitude and even sign. Electrolyte addition can interact with minerals in two different ways:

(1) Non-specific ion adsorption on mineral particles does not change the position but changes the magnitude of IEP. The addition of cations can compress the EDL of negatively charged hydrophobic mineral surfaces and shift the zeta potential to less negative values. The magnitude of negative charges can be lowered by adding a higher concentration of electrolyte.
(2) Specific ion adsorption changes the position of IEP and sometimes gives rise to charge sign reversal. Even a low concentration of the electrolyte can appear to compress the EDL if the cations of the added electrolytes show a particular adsorption on mineral surfaces, and a high concentration can result in charge sign reversal.

5.3.2 Mechanical energy input

In order to overcome the energy barrier, mechanical energy input (such as agitation, mixing, and high-intensity conditioning) can promote the collision and adhesion of tiny particles by providing external kinetic energy to particles for suspension.

5.3.3 Surface oxidation

Sulfide minerals are reactive and sensitive to extensive oxidation with air. Different sulfide minerals have different tendencies to oxidation for colloidal metal hydroxide formation on the mineral surfaces. The surface oxidation can occur during grinding or in atmospheric air. The presence of hydrogen peroxide (H_2O_2) can accelerate the oxidation process. However, polysulphate formation improved hydrophobicity and collectorless flotation of copper sulphate minerals [83].

The IEP of unoxidized sulphide minerals, such as pyrite (FeS_2), sphalerite (ZnS), chalcopyrite

($CuFeS_2$), and galena (PbS), has been determined to be between pH 1 and 2. These minerals are negatively charged across a broad pH range. These sulphide minerals exhibit a unique IEP of the metal oxides and act like the respective metal oxides during oxidation. For slime coatings, this sulfide-to-oxide conversion modifies the electrostatic interactions between sulfide minerals and clays [84].

5.3.4 Properties of the slimes

When slime coatings are controlled by electrostatic interactions, the electrical characteristic of the clay surface is crucial. In coal flotation, the presence of bentonite/montmorillonite, even in 2%, caused significant depression, but kaolinite and illite clays had little depression [85].

5.4 Mitigation technologies for slime coating

Adverse slime coating phenomenon in flotation can be mitigated by either chemical or physical means (Table 2). Slimes can be removed before or during the flotation process. Dispersant and clay binder additions are chemical removal methods; high-intensity conditioning, other coarse mineral additions, and wash water addition are physical removal methods during flotation and desliming, and ultrasonication is a physical removal method before flotation.

Table 2 Mitigation methods for slime coatings

Chemical slime removal technologies	Physical slime coating removal technologies
Addition of dispersants before flotation, Addition of clay binders before flotation.	High-intensity conditioning during flotation, Desliming before flotation, Ultrasonic treatment during flotation, Addition of another mineral during flotation, Wash water addition during flotation.

5.4.1 Dispersant addition

Mostly, anionic polymers are widely used to modify the colloidal interactions and modulate electrostatic and steric interactions between particles. In metallic mineral flotation, sodium silicate (Na_2SiO_3) is mostly used to depress silicate (SiO_2) and carbonaceous ($CaCO_3$, $MgCO_3$, $CaMg(CO_3)_2$) gangue minerals by adsorbing onto these gangue mineral surfaces and making them more hydrophilic. But Na_2SiO_3 is not very effective for coal gangue slimes. $SiO_3{}^{-2}$ and $HSiO_3{}^{-}$ ions adsorb on gangue minerals and electrostatically repel negatively charged minerals. Another anionic polymeric dispersant is carboxymethyl cellulose (CMC) for gangue dispersion with strong steric repulsion. CMC is effective in pentlandite-serpentine slime flotation, flourite-quartz/calcite slime flotation [4,86]. In flourite-kuvars/calcite flotation, CMC chemically adsorbs on fluorite and calcite surfaces at a pH of 9 and changes their surfaces to a negative charge. Thus, fluorite (CaF_2) and calcite ($CaCO_3$) repel each other. CMC does not adsorb on the quartz surface. There is a strong repel between quartz and fluorite.

5.4.2 Clay binder addition

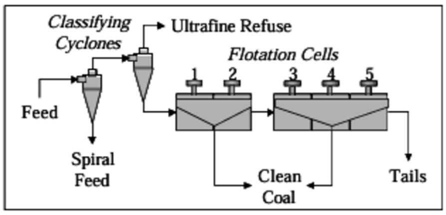
Clay binder dispersants enhance coal and phosphate flotation by agglomerating gangue clay minerals and removing them from the surface of phydophobic precious minerals. Clay binders are low molecular weight polymers that are condensed from urea and formaldehyde and reacted under an acidic environment. Clay binders adsorb both dipole-dipole interactions and strong H-bonds very selectively. Mitigation of the slime coating by clay binders was clearly validated [87, 88].

5.4.3 High-intensity conditioning (HIC)

Recovery and selectivity can be improved by increasing energy input in conditioning. Selective collector adsorption through quick diffusion, emulsification of oily collectors, and the formation of fine particle aggregates [89, 90], surface cleaning of hydrophobic minerals removes impurities from the surface [91–93]; and hydrodynamic forces decrease slime coating [92]. Kailuan Coal Mining Ltd. reported using HIC to remove slime coatings. But, detached slime particles after HIC may re-attach onto the mineral surface. However, separated slime particles following HIC may reattach to the mineral surface [94].

5.4.4 Desliming before flotation

Slimes harm flotation metallurgical performance, hence they should be removed before flotation by sieving or two-stage hydrocyclone classification. Desliming significantly improved pentlandite [91] and coal [95] flotation performance. Desliming in oxide mineral flotation is important. If there are both gangue and valuable slimes together, like in flourite flotation, a separate coarse and fine fraction flotation can be considered [96]. Figure 6 shows a two-stage cyclone desliming before the coal flotation circuit flowsheet for ash reduction. Fine fraction of the first hydrocyclone classified in the second hydrocyclone and underflow fraction (+325 mesh) is fed to the rougher coal floatation circuit. While ultrafine deslimed clay fines (-325 mesh) go to the tailing pond [59].



Solid content:	27%	→	19.7%
% of product mass	57.1% 36.7%	4.5% 1.2% 0.6%	
Conc. ash content	9.86% 9.22%	12.56% 16.25% 20.89%	
Conc. Mass %	56.9% 36.04%	4.72% 1.45% 0.90%	
Reagents in the flotation	frother and diesel/Kerosene		

Figure 6 Two-stage cyclone desliming coal feed to the flotation circuit

5.4.5 The ultrasonic pretreatment

Ultrasonic treatment removes clay gangue particles and increases flotation recovery. Çelik et al. [97] removed clay from boron minerals. Bandini et al. [75] removed Fe-oxide from the quartz surface in the presence of Calgon after ultrasonication, which applied extra mechanical force to remove Fe-oxides. Gurpınar et al. [98] achieved the complete removal of fine slimes previously coated on the barite particles. After creating a clean surface by ultrasonic pretreatment, microbubbles can be used to float hydrophobic particles.

5.4.6 Addition of other minerals

In pentlandite-serpentine flotation, the addition of coarse (-150+75 μm) quartz mitigated serpentine coatings and significantly improved Ni recovery [99]. Serpentine adsorbed on quartz more than pentlandite.

5.5 Entrapment

Entrained gangue particles can be trapped among bubbles/valuable particles attached to the walls of liquid channels/aggregates attached to bubbles [4, 11]. Such attached particles penetrate a significant distance into the channel, reducing the effective drainage path. Figure 7 shows the occurrence of entrapment from entrained gangue particles in the froth phase by water drainage and lamella thinning phenomena. According to Zheng et al. [15], entrapment occurs when the thickness of the froth lamellae and plateau borders approaches or falls below the particle size, preventing particles from draining freely. The process of trapping has the opposite impact as classification. Steric hindrance prevents particles that would ordinarily be categorized in the froth from returning to the pulp. Entrapment has been used to explain the increased concentrations of entrained particles in the concentrate compared to the pulp. Entrapment is only relevant when a number of process variables combine to enable such a steric impediment [11]. Kaya [4] discovered that entrapment increases with limited water recovery or when the foam gets dry. Introducing froth washing was effective in minimizing entrapment.

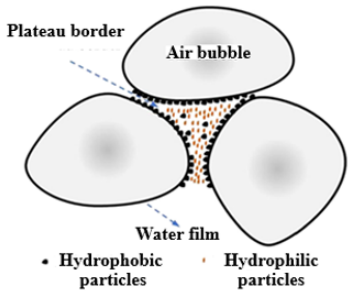


Figure 7 Occurrence of entrapment from entrainment among bubbles by water drainage in the froth phase

6 Froth washing technology in mechanical flotation machines

Entrainment is a non-selective process caused by the carryover of small particles with water, which reports to the froth launder and is a serious problem in froth flotation. Gangue rejection in the froth phase of mechanical flotation cells is mostly accomplished by physical mechanisms. In froth flotation, one of the most successful ways to reject weakly attached gangue particles from the froth and return them to the pulp phase is through froth washing.

In froth washing, as a drop of water falls into the froth, a mineral-loaded air bubble rises with entrained water (surround and wake) and fine particles. After interaction between a wash water drop and an air bubble, entrained particles drop/flow back into the pulp phase, while the bubble containing clean water attaches hydrophobic particles (Figure 8). Wash water drops or sprey create a downward counterflow to the entrained liquid rising the weakly attached or entained gangue particles out and flushes out back into the pulp. This cleaning improves the concentrate grade.

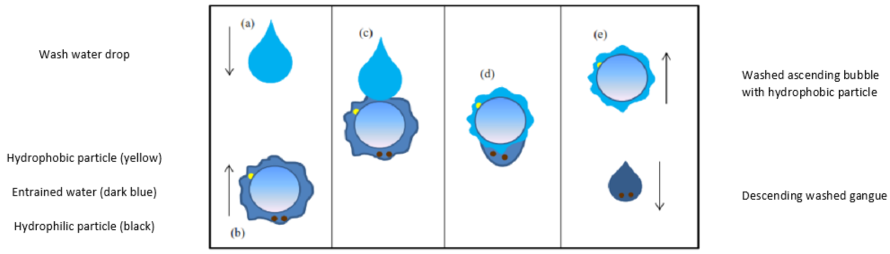


Figure 8 The froth washing mechanisms (a) drop of water descending into the froth, (b) mineral-laden air bubble rising in the froth with associated entrained water and particles (c) contact between the wash water and the air bubble, (d) the descending droplet of water displaces the entrained water and particles and, (e) entrained particles flow back into the pulp while the bubble with clean water ascends [66].

Wash water flushes out the gangue particles in the entrained liquid surrounding the ascending bubbles that make up the froth, creating a net downward flow of water [4, 65]. Froth washing should not alter or damage the froth structure. Froth washing directly affects bubble coalescence, froth drainage, froth stability, froth mobility, and froth rheology. Therefore, has a significant impact on both concentrate grade and recovery, reagent consumption, and cleaning stages required in froth flotation [4, 5, 59, 64, 65].

The wash water quality and quantity added to the froth phase is important. Fresh/potable water is better than recycled water. Fresh water does not contain contaminants, chemical residues, dissolved cations (Cu^{+2}, Fe^{+2}, Pb^{+}, Ca^{+2}, etc.), anions (F^{-}, ${SO_4}^{-2}$, etc.), and solid particles. High salt (Cl^{-}) in the water content may lead to equipment corrosion. Saline water (i.e., seawater) should not be preferred as wash water.

6.1 Model of hydraulic water balance in a flotation cell

Water recovery to the concentrate is important for gangue entrainment. One key element controlling water distribution is the froth phase and its structure. In order to quantify the interface transfer of water and air, superficial rates (J) (i.e., volumetric flow rates (Q) divided by the cell cross-sectional area (A)) can be useful. In modelling the water transport through the froth, it is assumed that bubbles leaving the pulp carry a sheath/envelope of water, which moves into the froth. The size of the bubble and the water sheath thickness are determined by surface tension and agitation parameters in the pulp. Water drainage back to the pulp is simulated using the example of bubble plateau borders in foams. The froth height is determined by the froth removal devices [4]. Figure 9 shows volumetric superficial flow rates (J = Q_{WW} (m^3/s)/A(m^2), m/s) definitions in and around the flotation cell and their calculation formulas for overall, froth zone, and pulp zone.

6.2 Water entrainment from the pulp to the froth phase

The number of bubbles rising per unit time ($6.Q_g/{d_{bp}}^3$) can be used to compute the volumetric flow rate of entrained water (Q_{cs}), where d_{bp} is the mean bubble diameter in the pulp zone and Q_g is the volumetric air flow rate. The volume of water in the froth is equal to $\mu.{d_{bp}}^2.\delta$, which

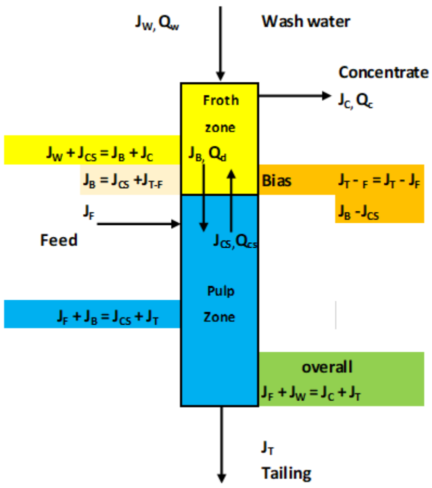


Figure 9 Water balance in and around the froth washed flotation cells [100] (J: superficial flow rates and Q: volumetric flow rates for each stream F: feed, C: concentrate, T: tailing, W: wash water, B: bias, and CS solids reporting to the concentrate).

is the volume of liquid contained by a film around a spherical bubble:

$$Q_{cs} = (6 \cdot Q_g \cdot \delta)/d_{bp} \tag{7}$$

Estimation of the bubble film thickness (δ) stems from a rigorous hydrodynamic and physico-chemical analysis of the flotation environment. Kaya [4] gives the following empirical formula for boundary layer thickness:

$$\delta = C_1 \cdot [(\mu^{0.25}/g^{0.33})] \cdot [(P_a/V_{lp})^{0.083}/V_t^{0.5}] \cdot d_{bp}^{0.833} \tag{8}$$

where,

μ: liquid viscosity, Nm/s

ρ: liquid density, kg/m^3

P$_a$: power input in aeration, W

V$_t$: bubble terminal velocity, m/s

C$_1$: adjustable constant

V$_{lp}$: instertitial upward liquid rate

$$V_{lp} = J_g/\epsilon_{bf} \tag{9}$$

where,

J$_g$: superficial gas rate, m/s

ϵ_{bf}: fractional gas hold up in the froth phase

Kaya [4] reported film thicknesses between 14μm and 40μm for 0.2 and 0.6 cm/s aeration rates in a modified laboratory Denver flotation cell without froth washing and 21μ and 46μm for 0.2 and 0.6 cm/s aeration rates with froth washing at 0.14 cm/s.

Steiner et al. [101] suggested the following equation for the amount of water passing upwards across a unit horizontal plane in unit time:

$$J_{cs} = J_g \cdot [(1 - \epsilon_{bf})/\epsilon_{bf}] \tag{10}$$

and the volumetric flow rate (Q$_{cs}$):

$$Q_{cs} = J_{cs} \cdot A \tag{11}$$

6.3 Water drainage from the froth to the pulp phase

The complicated phenomena of water draining from the froth have not gotten much attention in flotation. Drainage from the froth is crucial for secondary concentration in the froth, as noted by Mike and Feurstenau [102]. The description of drainage in solid-free froths has received a lot of attention. The whole downward flow can be written as follows, assuming that the walls of a boundary in froth are not entirely rigid [101]:

$$J_b = [(8.845 \cdot 10^{-3} \cdot \epsilon_{bf}^2 \cdot \rho_l \cdot g \cdot r^4)]/(\mu \cdot k_v \cdot d_{bp}^2) \tag{12}$$

Without wash water addition, J_b at the interface can be determined from the difference between J_{cs} and J_c.

$$J_b = J_g \cdot [(1 - \epsilon_{bf})/\epsilon_{bf}] + (J_w - J_c) \tag{13}$$

Drainage in the froth can be improved by increasing the aeration rate, liquid content of froth, and wash water addition, or decreasing the feed water going to the concentrate. The volumetric drainage rate (Q_d) can be calculated by:

$$Q_d = J_d \cdot A \tag{14}$$

6.4 Water into the concentrate

The concentrate flow rate can be modelled using the flow over a weir [103]. Francis' equation [104] was utilized to model this phenomenon by accounting for the gas present in the flotation froths. Velocity over weir:

$$V^2 = 2 \cdot g \cdot h \tag{15}$$

The following formula determines how much liquid is flowing over the weir:

$$Q_c = S \cdot \text{v} \tag{16}$$

where S: the cross-sectional area of flow above the weir, m^2.

By calculus, it can be shown that for a rectangular notch:

$$Q_c = 2/3 \cdot [W \cdot (2 \cdot g \cdot H^3)^{0.5}] \tag{17}$$

In reality, it is discovered that Eq. 17 overestimates Qc due to streamline contraction and frictional losses. To take losses and gas holdup into consideration, Eq. 17 might be modified as follows [4]:

$$Q_c = J_c \cdot A = 2/3 \cdot (K_c \cdot W \cdot (2 \cdot g \cdot H^3)^{0.5}(1 - \epsilon_{bf}) \tag{18}$$

Where,

W: the width of the flotation cell lip, m.

H: vertical distance between the froth surface and cell lip, m

Q_c: volumetric liquid flow rate to the concentrate, m^3/s

J_c: superficial liquid rate going to the concentrate, m/s

K_c: discharge coefficient, which is influenced by the kind of removal method employed, froth viscosity, solid percentage, gas holdup, etc.

The net downward flow of water through the froth, or its counterpart, the net difference of water flow between the tailings and feed, is another definition of the bais rate, J_B (as a surface velocity). Q_W is the wash water addition rate in m^3/s, and A is the cross-sectional area of the cell in m^2. $J_B$can be calculated from J_{CS} minus J_{T-F}.

Wash water ratio

$$W = Q_w/Q_c \tag{19}$$

where, Q_c: the rate of the water flow in the concentrate. Best W should be in the range of 0.5 and 1.0.

J_{cs}/J_Fcan be considered as an entrainment factor, and J_B/J_T can be considered as a drainage factor.

Bias can be calculated as

$$J_B - J_{CS},\ J_T - J_F,\ or J_w - J_c \tag{20}$$

At constant J_F and J_W, with an increase in superficial gas rate (J_g), froth thickness (FT), entrainment factor, and drainage factor increase, and bias decreases. At constant J_F, $J_{W,}$ and

FT, with increasing J_g, entrainment and drainage factors increase and bais decreases. Bias flux is the difference between the wash water flux and product water flux. Bias flux can be negative (upward), zero (neutral), or positive (downward) in terms of the net liquid flow direction relative to ascending bubbles. If no wash water is used, the bias is negative, and gangue recovery is dominated by entrainment. At neutral and positive bias, wash water is added. At zero bias, where the net liquid flow is neutral, the wash water ratio is 1, bulk entrainment is drastically minimised, and bubble surface entrainment becomes the principal mechanism. If the bias is positive, the wash water ratio is greater than 1, and the downward liquid flow effectively washes some of the gangue particles from the bubble surfaces, thereby reducing gangue recovery to a minimum. The concentrate grade is deteriorated by the use of negative bais. Feed water recovery is strongly affected by bias and feed rate.

Part of the wash water flows downward through froth and eventually exits with tailings; this is called bias flow. The balance of the wash water reports to the overflow. Bias superficial flow J_B is typically 0.02-0.1 cm/s in column flotation [100] and 0.035-0.135 cm/s in conventional lab cells [4]. The froth is stabilised by the bias water, permitting deep froths even in the absence of solids. Excessive bias rate ($J_B > 0.3$ cm/s) causes mixing in the upper froth zone, decreases retention time, and loss of cleaning. Bias rate should be as low as possible to minimise water consumption and maximise pulp zone retention time. Deep froths, based on solids loading conditions, promote selectivity because of detachment and reattachment with the froth. Each froth exhibits a maximum solid carrying capacity based on feed particle size and density. Salt presence in wash water promotes particle aggregation and enhances washability [105].

Maachar and Dobby [27] suggested the following empirical equations for feed water (R_{FW}) and solids recovery (E_s) by entrainment in a laboratory column:

$$R_{FW} = 2.58 J_f^{-1} \cdot exp(-13.1 J_w - J_c) \tag{21}$$

$$E_s = 2.58 J_f^{-1} \cdot exp(-0.0325 \Delta\rho) \cdot exp(-0.063 d_p) \cdot exp(-13.1 J_w - J_c) \tag{22}$$

where,

J_f: superficial feed rate, cm/s

d_p: particle diameter, μm

$\Delta\rho$: specific gravity difference between the solid and the water, g/cm^3

Particle size, specific gravity of solids, and operating parameters (such as superficial feed rate, wash water rate, and concentrate rate) all have an impact on solids recovery through entrainment. It can be reduced by increasing the bias rate, particle size, and density.

6.5 Gas balance in a flotation cell

The gas balance for the froth phase can be expressed as follows, assuming that there is no gas loss in the pulp phase and gas pick-up from the froth surface:

$$J_g = J_{ac} + J_a \tag{23}$$

where,

J_{ac}: superficial gas rate associated with liquid transfer to the concentrate, cm/s

J_a: superficial gas rate directly going to the atmosphere by bursting at the top of the froth phase (collapse), cm/s

Kaya [4] presented the following formula for superficial gas flow rate with liquid transfer into the overflow weir (J_{ac});

$$J_{ac} = J_c \cdot [\epsilon_{bf}/(1 - \epsilon_{bf})] \; and \; Q_{ac} \tag{24}$$

$$Q_{ac} = J_{ac} \cdot A \tag{25}$$

where,

Q_{ac}: volumetric air plus liquid flow rate of the froth flowing over the concentrate weir, m^3/s.

Q_{ac} is related to the width, depth, and viscosity of the concentrate stream as it flows over the concentrate weir.

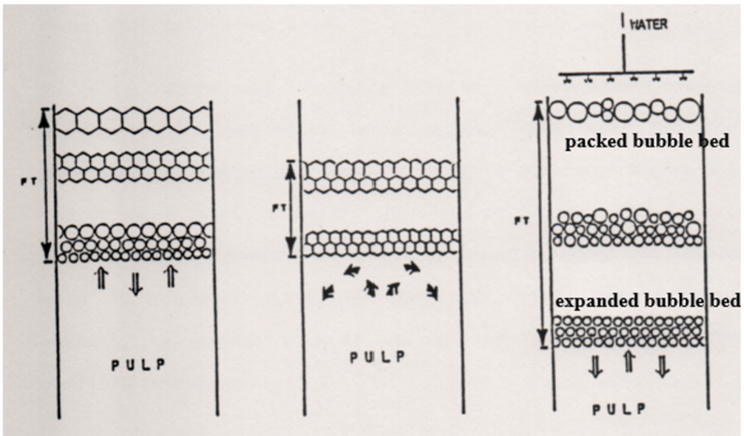
Generally, increasing J_{ac} favours recovery and increasing J_a favours grade [4]. From the above equations, J_b can be rewritten:

$$J_b = J_a \cdot (\epsilon_{lf}/\epsilon_{bf}) + J_w \tag{26}$$

In order to reduce entrainment, the drainage rate can be raised by increasing gas escape to the environment (i.e., improving bubble collapse at the top of the froth). In shallow froths where particle reattachment is challenging, bubble rupture can be minimized to avoid unstable froth production and valuable particle loss. These two goals obviously compete when wash water is not added. But, wash water addition both increases water drainage to reduce entrainment and reduces froth instability by increasing inter-bubble water thickness.

6.6 Structure of the froth

The froth phase in mechanical flotation cells starts from the pulp-froth interface to the froth top. Rectangular mechanical flotation cells overflow either one or two sides with or without froth paddles. Circular mechanical cells overflow from all over the periphery of the cell. Some flotation machines have both outer and inner overflow launders to increase recovery. Flotation recovery can be increased by increasing cell lip length (LL) and froth thickness (FT), which are generally determined by the cell manufacturers. Flotation recovery is mainly affected by operating variables of J_g, J_w, impeller rpm, frother dosage, and % solids. Three different froth structures were encountered in flotation. Draining froth, polyhedral froth, and washed froth (Figure 10). Less entrainment and coalescence, more drainage, stable and easily moving deep froth can be easily produced by froth washing. At the top of the froth, there is a packed bubble bed (gas holdup $> 74\%$), and at the pulp-froth interface, there is an expanded bubble bed (gas holdup $< 74\%$). Between packed and expanded bubble beds, there is a draining froth. Gangue entrainment in the inter-bubble water is increased in wetter froths because the spherical bubbles occupy the available space less effectively than the bigger polyhedral bubbles of drier froths [4]. Bubbles in a washed froth are well separated from one another, and a net downward water flow rate encourages gangue drainage between bubbles.



Draining froth	Polyhedral froth	Washed froth
More entrainment	Less entrainment	Less entrainment
More coalescence	More coalescence	Less coalescence
More drainage	Less drainage	More drainage
Not very stable	Not stable	Very stable
Difficult to remove	Difficult to remove	Move easily
Easy to produce	Difficult to produce	Produced easily
Shallow froth	Shallow froth	Deep froth

Figure 10 Three different froth structures encountered in flotation cells [4]

Froth can expand significantly with good stability if there is a positive bias. Drainage channels make it simple to stop feed water penetration and return it to the pulp zone. If wash water is introduced a few centimetres below the top of the froth surface, a polyhedral bubble zone may form at the top of the washed froths, but this may not be beneficial. Polyhedral bubbles are invisible if it is added above the froth surface. Washed froths produce the finest mass transfer characteristics of tiny spherical bubbles without the drawback of increased entrainment, according to a comparison of the three froth architectures [4, 106].

Kaya [4] suggested the following equation for maximum froth thickness (FT_{max}) calculation in mechanical cells with wash water addition:

$$FT_{max} = -0.34 - 308 \cdot 6J_w^2 + 66.4J_g + 1078 \cdot 1J_w^2 \cdot J_g \tag{27}$$

where,

J_w: superficial wash water rate, cm/s

J_g: superficial gas rate, cm/s

FT_{max}: maximum froth thickness, cm

Kaya [4] developed the following empirical equation for superficial concentrate rate (J_c) from laboratory mechanical cell data in the presence of wash water addition:

$$J_c = 0.00061 - 0.0088T + 0.00196H^{1.5} + 0.0408J_g + 0.01899J_w \quad (28)$$

where,

J_c: concentrate superficial rate, cm/s

T: the distance between pulp-froth interface and cell overflow weir, cm

H: The distance between overflow weir and froth top, cm

6.7 Stability of the froth

The stability of froth is crucial for the selective separation of hydrophobic and hydrophilic particles in flotation. The capacity of air bubbles in froths to withstand coalescence and rupture is known as froth stability. Hydrophobic particles may separate from air bubbles in unstable froths, reducing recovery rates. Overly stable froths, however, have the potential to entrain hydrophilic particles, which could lead to a poorer concentrate grade even though it increases the recovery rate.

The lamellae are crucial for froth stability. The surfaces of air bubbles are called lamellae, and thin coatings divide adjacent air bubbles. The majority of the foam's liquid content travels via the Plateau boundary, where three lamellae converge at a 120° angle, with a smaller portion staying inside the lamellae. Liquid in the froth drains toward the slurry layer along the Plateau boundaries during flotation due to gravity. Froths can be dry or wet according to the moisture content. If volumetric liquid content is higher than 36%, the froth is considered wet. In flotation, wet froth is at the bottom layer, and dry froth is at the top of the froth. In dry froth, bubbles are in polyhedral shape [107].

There are two types of mineralised froths in flotation: highly mineralised and partially mineralised froths. Highly mineralised froth can be spherical or polygonal in shape. These froths are dry, voluminous, closely knit, and persistent. All the bubble surfaces are loaded with hydrophobic minerals, yielding higher recoveries. Coal and some industrial minerals have this type of froth. Partially mineralised small-bubbled, loosely knit, spherical, and brittle froths carry hydrophobic particles only at the bottom part of the bubble and are watery/fizzy and very fragile for bursting. Low-grade metallik ores can give this type of froths yielding high concentrate grades [4, 108].

The goal of commercial flotation monitoring systems that use machine vision and image processing is to create a relationship between flotation performance indicators and visual froth stability characteristics. The link between visible froth characteristics and flotation performance currently lacks a defined model. Empirical regression models make up the majority of flotation models based on visual information in images. These models, however, work best over brief periods of time. However, these systems' poor accuracy and costly maintenance requirements have prevented them from being used in more industrial settings [107].

6.8 Mean retention time (MRT) determination

6.8.1 Liquid mean retention time in the slurry phase

There are two possible approaches. Samples are periodically taken from the tailing stream in the first approach, which involves adding a water-soluble tracer to the input stream. The tracer response curve is used to calculate the retention time distribution (RTD) to estimate the MRT. LiCl's low cost, unreactiveness, water solubility, and ease of AAS analysis make it suitable for use as a liquid tracer. The tailing flow rate and gas holdup are measured using the second method [106]. Average gas holdup is determined by measuring conductivity with an electrode assembly.

MRT of the liquid in the slurry phase τ_{lp} is equal to

$$\tau_{lp} = (V_p \cdot \epsilon_{lp})/Q_t = SH \cdot \epsilon_{lp}/J_t \quad (29)$$

where,

V_p: slurry volume, m^3

ϵ_{lp}: volumetric liquid holdup in the slurry phase, %

SH: slurry height, m

J_t: superficial tailing rate, cm/s

τ_{lp}: mean retention time of the liquid in the slurry phase, s

Q_t: volumetric tailing flow rate, m^3/s

6.8.2 Solids mean retention time in the slurry phase

RTD's of solid particles (τ) can be determined by radioactive tracer tests [109]. In perfectly mixed systems following equations can be used:

$$E\left(t\right) = \frac{C\left(t\right)}{\int C\left(t\right).dt} = \frac{1}{\tau}\, e^{-t/\tau} \tag{30}$$

$$lnA = ln = \left(\frac{1}{\tau} - \frac{t}{\tau}\right) \tag{31}$$

where, C: amount of tracer reporting to the tails in time t, kg

6.8.3 Gas and liquid retention time in froth

Assuming a constant gas holdup in the froth phase, the MRT of gas and liquid in the froth phase (τ_{bf}= τ_{lf}) is equal to:

$$\tau bf = \frac{Vf.\epsilon bf}{Qg} = \frac{FT.\epsilon bf}{Jg} \tag{32}$$

$$Vbf = \frac{FT}{\tau bf} \tag{33}$$

where,

V_f: froth volume, m^3

ϵ_{bf}: fractional gas holdup in the froth phase

Q_g: air flow rate, m^3/s

V_{bf}: average bubble rise velocity in the froth phase, m/s.

6.9 Froth Recovery, Froth Carrying Capacity, and Cell Lip Loading

Zanin et al. [110] suggested the following equation for froth recovery (R_f):

$$R_f = e^{-\beta\left(\frac{\tau}{T_{0.5}}\right)} \tag{34}$$

Where,

τ: average froth retention time, s

$T_{0.5}$: time needed for the froth to collapse to 50% of its initial equilibrium, s

β: Constant for given physical and chemical properties of froth

Lip length (LL) is characterized by the quantity of dry solids concentrate recovered per given length, while froth carrying capacity (FRC) is defined by the dry mass of concentrate taken from the cell per given area of the froth per time:

$$\text{FRC} = \text{Solids in product (tph)/Froth surface area (m}^2\text{)} \tag{35}$$

$$\text{LL} = \text{Solids in product (tph)/Lip length (m)} \tag{36}$$

By applying the aforementioned formulas to determine the appropriate FRC and LL, flotation cell designers may maximize froth movement in the cells at any stage. A high concentrate flow rate and continuously flowing froth are necessary to generate a large froth surface area and LL to control the high flows in roughers and cleaners. On the other hand, less froth surface area and LL are needed in scavenger cells for low-concentration flow and delicate froths to guarantee that the froth reaches the launder. For mechanical flotation cells, the lip loading should be kept below 1.5 t/m/h after the FRC is deemed satisfactory. Different launder configurations have different lip lengths. FRC rates for a bank of mechanical cells, without wash water addition reported between 0.8-1.5 for rougher, 0.3-0.8 for scavengers, and 1.0-2.0 tph/m^2 for cleaner circuits as a rule of thumb by industry [58].

6.10 Physical froth flow modifiers

There are four types of froth flow modifiers: launders, froth discharge pedals, froth crowders, and baffles. These modifiers provide a cost-effective solution to solve the problems associated with froth mobility in large flotation cells. They enhance froth recovery by facilitating froth transport.

6.10.1 Launders

Launders directs the froth formed in the cell to a concentrate weir. They exist in the form of channels/inclined drainage channels into which the froth overflows and is directed to the concentrate weir. Launders can be internal and external. Internal launders eliminate dead zones by reducing the froth discharge distance. But, internal launders reduce cell volume and require additional installation support. External launders are easily designed and installed. They provide the greatest collecting surface area and do not consume cell volume. But external launders result in more footprint of the bank. For circular cells, external peripheral/concentric launders and/or internal launder discharge launders can be used. For flow in the launders, a slope of 10-15^{o}is used. Internal launders reduce the froth volume to some extent. External launders do not affect the froth recovery and froth carrying capacity. Rectangular cells use one/two sides of discharge launders. Other types of launders are radial, central donut, transverse launders for internal discharge, and hexagonal launders with crowder for external peripheral launders [58].

For a bank of cells, first cells recover about 70-80% of the valuable mass in the feed, and the last cells recover 20-30% of the concentrate. Therefore, in the first cells, a large froth surface area with a longer lip length and external launders should be used. For the last cells, lower lip level and donut type launders should be preferred. For low-grade ores, the froth carrying capacity is low; thus, additional launders are needed to reduce the froth surface area and increase the froth carrying capacity. For large cells, the froth travel distance is high. Thus, froth may build up, causing immobility and leading to collapse. In large cells, froth retention time should be reduced by inserting extra launders to eliminate dead zones at the back of the cell [58].

6.10.2 Paddles/Scrapers

Froth paddles/scrapers mechanically and quickly remove heavily-loaded/ immobile top froth into the concentrate launder. They are placed cell discharge side and their revolving blade immerses a few centimeters below the cell lip for not to disturb the underlying froth structure. Paddles revolve with a small rpm. They remove slow-moving, fast-forming, or viscous froths. Froth paddles increase froth mobility and induce froth drainage. Froth drainage improves the grade. Paddles reduce the froth retention time and induce agitation and mixing in the froth zone. This may reduce the recovery of large particles. Froth paddles can be flat, helical, or full surface scraper type. For coal flotation, about 80% of the feed floats easily; thus, this froth must be removed as quickly as possible before colapsing. Froth paddles are required for coal froth removal [58].

6.10.3 Froth Crowders

Crowders accelerate froth discharge velocity for fragile froths and improve froth removal dynamics. Froth crowders significantly enhance froth recovery. Industrial-scale froth crowders are mainly used in cylindrical cells rather than rectangular cells. Booster cone, freely rotating cone, built-in crowders, and adjustable radial crowders are used in cylindrical cells. A fixed crowder/diverter at the back of the cell is used in rectangular cells. Froth crowders improve froth removal dynamics, eliminate dead zones, some of them are adjusted up and down to increase froth carrying capacity when feed grade varies, and some of them have both froth crowding and froth skimming functions. Froth crowders can have a truncated conical shape, a trapozoidal shape, a multi-layered conical shape, or any other shape. Disadvantages of froth crowders include the requirement of additional mechanical lifting to adjust their depth, frequent requirement for cleaning, some of them are fixed, and some require complicated rotor designs and automation [58].

Even at the fast-floating stage of the flotation bank, such as the initial roughers and final cleaner flotation cells, the employment of periphery launders in combination with froth crowders speeds up froth discharge without the need for froth paddles. Crowders are helpful at every stage of the flotation circuit; for example, a plant can use a flotation cell equipped with a crowder during the scavenging, cleaning, or roughing stages without impeding the recovery of froth.

6.10.4 Froth baffles

These flow modifiers divert the bubbles entering the froth near the concentrate weir to the center of the cell for increasing retention time in the froth phase. Froth baffles also activate dead zones. The use of froth baffles will enhance both grade and recovery to some extent. Baffles may encourage bubble coalescence, which may lead to a decrease in coarse and middling particles recovery [53]. Wemco-Leeds Column used rod barriers. Rod barriers' stripping effect lowers the amount of trapped or loosely held material, mostly gangue, attached to the air bubble, improving the concentrate's grade [57].

7 Froth Washing in Mechanical Flotation Cells: Laboratory, Pilot, and Industrial Trials and Applications

Froth washing was first applied in Russian bituminous coal flotation at Karagandinskaia plant using showers at the beginning of the 1960s. Froth washing increased coal recovery from 2.45% to 11.8% and decreased ash content from 14.1% to 1.9% [111]. In tungsten (W)-molybdenum (Mo) column flotation, wash water was added using perforated pipes. A 10-15% increase in concentrate grade for andalusite flotation and a 2.7% to 7.2% increase in Mo content during cleaning stages of powellite ore flotation at Lyangarska plant were reported by Klassen and Makrousov [111].

Miller [56] recommended using froth washing in conjunction with a brief retention period to clean coal froth. He discovered that the single-stage addition of wash water is a feasible substitute for roughing and cleaning after comparing the flotation product produced by adding wash water to a single stage with that of the conventional rougher-cleaner system. Until 1985, there was no literature about the testing and use of froth washing in laboratory or industrial froth flotation plants. With the development of column flotation in Canada, froth washing in pneumatic column flotation machines to reduce gang recovery has been a standard concept since 1985. For the existing industrial-scale operations, the use of the froth washing concept in the conventional flotation machines was a much cheaper alternative than the installation of new flotation columns.

7.1 Froth washing for low-grade metallic ores

Kaya [4] showed first time that it was possible to use froth washing in laboratory, pilot, and industrial scale mechanical flotation machines for low-grade metallic sulphide and oxide ores. After Kaya's fundamental froth washing study at McGill University between 1985 and 1989, froth washing in mechanical flotation machine trials and tests increased significantly and gained importance. Previous froth washing test conditions and obtained improved metallurgical results are summarised in Table 3. Froth washing minimises the nonselective entrainment of ultrafine minerals into the froth phase. Froth cleaning by wash water in mechanical cells was quantitatively first determined from laboratory to industrial scales in some Canadian, Australian, and the USA plants. Kaya and Laplante [12, 112] developed froth washing technology in mechanical flotation cells and brought it first to the stage of plant implementation in the 1990s. Kaya [4] tested the effect of wash water addition and assessed the potential improvements in the existing Stratcona Cu-Ni plant in Sudbury, Canada. The major problem for the Stratcona concentrator was the separation efficiency between copper (Cu)-phyrotite (Po), nickel (Ni)-Po, and Ni-Cu separation. Cu ore was chalcopyrite ($CuFeS_2$), Ni ore was pentlandite $(Fe, Ni)_9S_8$, nickelliferrous phyrotite (Fe_7S_8) with 0.2% to 1.2% Ni content. Monoclinic Po was magnetic and could be separated by a magnetic separator. But hexagonal Po wasetic and floated well in neutral pH values. Gangue minerals were feldspar, quartz, mica, talc, and chlorite. Valuable massive sulphate minerals were disseminated in the host rocks.

Table 3 Summary of the laboratory, pilot-plant, and industrial-scale froth washing test conditions, details, and results

Froth washing test	Froth Washing Conditions	Froth Washing Results
Laboratory-scale modified plexiglass cell, McGill University, Canada. Denver D1 cell, 6.5 L; 15×15×32 cm; 1500 rpm; FT: 4 cm; SH: 30 cm; J_g: 0.6 cm/s; J_w: 0–0.11 cm/s; Denver D-8 mechanical flotation machine; spiral perforated copper wash water distributor for entire froth surface.	The optimum wash water addition rate is between 0.03 and 0.07 cm/s. Excess wash water rate is not attractive due to the increased water requirements and excessive pulp dilution. Excess wash water also increases gangue recovery due to froth mixing, bubble breakage, and bed collapse.	The entire froth surface should be washed evenly and gently with perforated pipe types of distributors. Froth washing can reduce entrainment by more than 50% [113].
Laboratory-scale flotation column. Plexiglass; d: 3.8 cm, h: 2 m; v: 2.3 L; FT: 30 cm; SH: 170 cm; J_g: 1.2 cm/s; J_w: 0.8 cm/s; sparger: ceramic; spiral copper pipe wash water distributor for entire froth surface.	The entire froth surface should be washed evenly and gently with perforated pipe types of distributors. 30 cm froth thickness is adequate for froth cleaning.	Column flotation operated under present circuit conditions did not offer any advantage over the conventional cells (without wash water addition) used in the non-mag circuit [114, 115].

continued on next page

Froth washing test	Froth Washing Conditions	Froth Washing Results
Pilot-scale, McGill University, Canada. Denver D6 cell, 65 L; 40×40×45 cm; 600 rpm; FT: 9–15 cm; SH: 37 cm; J_g: 1.03 cm/s; J_w: 0–0.089 cm/s; Denver D-8 mechanical flotation machine; straight perforated copper wash water distributor and/or spray nozzle for entire froth surface.	Tracer and conductivity tests confirmed that there was a minimum feed water penetration at an intermediate wash water rate. Higher gas rates have deleterious effects on froth washing capacity. Falconbridge Stratcone Cu-Ni ore was used in the pilot-scale froth washing tests.	For Cu-Ni ore, wash water significantly decreased gangue entrainment and increased concentrate recovery. Washing water stabilized the froth phase and increased recovery. Rejection of free gangue was easy, but locked and/or partially hydrophobic particle rejection depended on the nature of solids (i.e., particle size, hydrophobicity, population density, etc.), froth stability, froth wetness, and wash pattern. Due to the relatively coarse nature of the Cu-Ni feed, the effect of wash water was much more clearly observed in the -37 μm fraction [113].
Industrial-scale trials. Falconbridge, Stratcone Ni-Cu sulphide ore, Non-magnetic pyrrhotite circuit, Canada, ON. 6 in a bank and 6+4 in two banks. Open flow Denver D30 cell (each 2.8 m^3) design. No froth paddles. Average retention time: 10 min. One/front side overflows without froth paddles. Froth character: Brittle. Froth thickness: 30 cm. F80: 75 μm. Two plant trials at different times were carried out at the non-mag circuit with and without wash water addition. In the first trial, bank performance and in the second trial, circuit performance were determined. Test trials: Short-term (10-day period).	Falconbridge Ni-Cu Plant, Canada. J_w: 0–0.085 cm/s. Number of cells in each bank: 6 and (6+4). Perforated portable plastic wash water pipe diameter: 1.9 cm. Hole diameter: 1–3 mm. Hole interval: 1 cm. Number of pipes in each cell: 2–4. Number of holes on perforated pipes: 70–280. Perforated pipe distance above the froth surface: 45 cm and 15 cm. Total wash water flow rate: 320 L/min. Wash water pressure: 21 PSI. Optimum wash water flow rate of 0.05 cm/s requires water consumption of 5–15% of the feed water entering the bank. Perforated pipe distributors for watery froth were better than spray nozzles, which minimize water requirement near the overflow weir.	Falconbridge Ni-Cu Plant, Canada. Cumulative Ni and Cu grade increased 43% and 38%, respectively, with wash water (J_w: 0.033 cm/s) at lower recoveries. Gn and Po recoveries were decreased 48% and 15% with wash water, respectively. Conventional flotation always outperformed column flotation with and without wash water addition in Ni upgrading and Po rejection. Front-side washing with two pipes at J_w: 0.055 cm/s achieved significantly higher cumulative Ni and Cu grades at substantially lower Gn and Po grades. Ni grade increased from 1.47% to 2.15% and recovery from 85% to 87%. At the same Ni recovery, wash water decreased Gn recovery by half, and Po recovery by about 25%. Wash water easily flushed out free gang particles, which followed the water, and locked or naturally hydrophobic Po particles were difficult to suppress. Washing the front froth surface was better than washing the entire froth surface. Upgrading Ni and Cu and rejection of Po and Gn in the froth were verified by the froth grade profile with froth washing. Washing the front surface of the froth with 2 pipes was better than washing the entire froth surface with 4 pipes [116, 117].
Eastmaque Gold Mines, Au tailing reclamation, Kirkland Lake, Quebec, Canada. Historical mine tailing in the lake bottom (14 m depth) with 1.4 g/t Au content. Tailing contains pyrite with Au and silica gangue. The second Au cleaner bank with 4 Denver D30 (2.8 m^3) open flow cells is used in plant testing. F80: 45 μm. Froth paddles are present. Overall plant performance was evaluated with and without wash water addition. Test trials: Short-term (10-day period).	Eastmaque Gold Mines. J_w: 0–0.05 cm/s. Number of cells in the bank: 4. Perforated wash water pipe diameter: 1.9 cm. Hole diameter: 1–3 mm. Hole interval: 1 cm. Number of pipes in each cell: 1–2. Number of holes on perforated pipes: 280–70. Perforated pipe distance to the froth surface: 15 cm. Wash water pipes placed behind the froth paddles. Wash water consumption for the bank: 63 L/min.	Eastmaque Gold Mines. Final concentrate Au grade increased from 2.33 oz/t to 2.66 oz/t with wash water addition at a slightly higher recovery (1.2%). With wash water, the percentage of -10 μm is significantly lower. Fines return to the first cleaner, and then rougher and scavengers. Since the wash water is added to the last stage of cleaning, there was no flotation capacity reduction, and also no problem with thickening and filtration. Wash water addition reduced feed water recovery from 78% to 33% and fine gangue recovery (-10 μm) from 65% down to 15%. Froth washing with 2 pipes is better than 1 pipe. The single pipe achieved a 23% higher grade at the expense of a 10% recovery decrease. The addition of warm wash water (45°C) increased the Au grade from room temperature wash water. Based on test trials, wash water was implemented in the 2nd Au cleaner bank at the beginning of 1989 [117].
Les Mines Selbaie, Cu-Zn-Ag sulphide ore, Joutel, Quebec, Canada. 12 froth washing tests were performed at the 2nd & 3rd Zn and 3rd and 4th Cu cleaning banks. A total 3+3 and 2+1 OK-3 open flow cells were washed to evaluate the bank and plant froth washing amenability. 35–45% solid use in the plant necessitated wash water addition, not only for froth washing but also pulp dilution. F80: 25 μm. Froth thickness: 10–20 cm. Bank and plant performance were evaluated. Test trials: Short-term (1-day period).	J_w: 0–0.085 cm/s. Number of cells in the bank: 3+3 and 2+1. Perforated wash water pipe diameter: 1.9 cm. Hole diameter: 1–3 mm. Hole interval: 1 cm. Number of pipes in each cell: 2. Number of holes on perforated pipes: 280–70. Perforated pipe distance to the froth surface: 15 cm. Wash water pipes placed behind the froth paddles. Wash water flow rate: 95–163 L/min for six cells.	With a 42 L/min wash water flow rate for 3 cells, Cu grade increased from 22.7% to 25.6% and recovery from 47% to 51%. For the Zn circuit, the best metallurgical performance was achieved at a 95 L/min wash water rate with 6 cells. Final Zn grade increased from 51.6% to 55.3% at a 1% higher recovery. Increasing froth thickness (5–8 cm) in the Zn circuit with froth washing achieved the best Zn metallurgy. Grade increased from 50.9% to 56.1% and recovery from 89% to 90%. A very high wash water flow rate decreased both Cu grade and recovery, and significantly increased Zn grade at the expense of recovery. Since the theoretical maximum grades to be achieved with this type of ore are very close to the reported assays here, it can be assumed that gangue rejection with froth washing is almost complete. Long-term normal plant performance without froth washing was 24.5% Cu and 54.5% Zn. During plant trials, the plant was processing ore containing a significant amount of slimy limonite. Even under these hard conditions, froth washing achieved a 1.4% increase in Cu and 1.6% increase in Zn grades [116, 118].
Zinc Corporation of America (ZCA), Zn-Pb sulphide ore, New York, USA. Long-term plant-scale froth washing tests were performed by the ZCA at the Zn cleaners. The objectives were to reduce the light element oxides (MgO, CaO and SiO_2), to increase the Zn grade in the final grade, and dilute the pulp phase. Froth thickness: 30–40 cm. Test trials: Short-term (10-day period), Long term (45-day period).	J_w: 0.05 cm/s. Number of cells in the bank: 4. Wash water pipe diameter: 1.9 cm. 3 spray nozzles in each pipe system were used. Number of pipes with spray nozzle in each cell: 2. Wash water pipe distance to the froth surface: 30 cm. Wash water pipes placed behind the froth paddles. Wash water consumption for each cell: 41.6 L/min.	After froth washing plant trials, Zn grade increased from 55% to 56.8% at constant recovery, while gangue grade decreased from 6% to 4% during a 45-day froth washing application with spray nozzles. Four 2.8 m^3 Denver cells were washed with six spray nozzles per cell. A wash water spray system was permanently installed, equipped with spray nozzles to wash the front part of 9 m^3 Cleaner and rougher Denver cells to suppress the voluminous froth. At ZCA, it was observed that bubbles on the top layer of the froth were smaller and spherical with wash water as compared to larger and polyhedral without it [119].
Les Mines Niobec, Nb oxide ore, Canada. Froth washing tests at the 1st (three 9 m^3 Denver) and 2nd (two 9 m^3 Denver) carbonate cleaner banks were performed to minimize Nb_2O_5 loss in the concentrate. Test trials: Short-term (10-day period).		The lowest Nb_2O_5 loss in the carbonate concentrate was achieved at wash water flow rates of 150/77 and 159/100 L/min for the 1st/2nd cleaners. Without wash water addition, the Nb_2O_5 loss was 0.25%; with wash water addition, 0.165% [116, 118].
Goedehoop South (GHS), S. Africa Coal Plant. The effect of froth lip washing was determined and compared with baseline values without froth washing values at the same time. The effect of reagent dosage, particle size, and different coal qualities was determined in a plant-scale.	Tests were performed on two identical flotation lines with wash water and without wash water addition. Circular HDPE pipe ring (ID: 16 mm), 4 mm holes at 1 cm intervals. 10 cm over the cell lip. 4.5 m^3/h wash water flow rate. Feed density: 1.022 t/m^3, feed flow rate: 200 m^3/h. Air flow rate: 51 m^3/h, J_g: 0.98 cm/s. Reagent dosage: 1.3 kg/t solid feed. High-quality and low-quality coal feeds were used separately. A 20% frother (CGH7)+80% collector (CGM4) ratio were used.	Coal yield improvement about 15%. An increase in reagent dosage increased the yield at higher ash content. 1.30 and 1.45 kg/t reagent dosages achieved both higher yield and lower ash content. Froth washing achieved a better yield and similar ash content between 75 μm and 300 μm particle size. The optimum coal flotation size was 75–300 μm. An increase in the yield was obtained with froth washing for both high and low-quality coal feeds. Increase in yield for low-quality coals (23.3%) was higher than high quality coals (7.9%). Ash content of low-quality coal (37.7%) is clearly higher than high quality coal (32.3%). Lip washing is significant for both low-quality and high-quality coal processing. Lip washing will become more important as high-quality coal reserves get depleted [120].

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Froth washing test	Froth Washing Conditions	Froth Washing Results
Arizona Copper Concentrator, USA. Cyprus-Bagdad plant trial and operating experience. 3 cell Wemco-Leeds column (3.4 m^3) versus 6 cell Agitair mechanical cells (2.83 m^3). 6 Agitair conventional cells versus 6 Wemco-Leeds Column (2.83 m^3). 6 Agitair + 6 Agitair conventional cells (2.8 m^3) versus 6 Wemco-Leeds + 6 Wemco-Leeds cells (2.8 m^3) in parallel.	Plant test in the first and secondary cleaners. Second cleaners. First and second cleaners. The concentration ratio was used for comparison due to significant feed grade variation during the tests. Rod barriers created a severe scaling problem for free movement.	In the secondary cleaner, Wemco-Leeds Column: 32.95% Cu, 0.63% Mo, 3.39% insoluble grades; Conventional flotation: 31.6% Cu, 0.61% Mo, and 5.79% insoluble. First cleaner, Wemco Leeds Column: 30.76% Cu, 1.83% Mo, and 3.7% insoluble; Conventional flotation: 31.09% Cu, 1.4% Mo, 6.67% insoluble. 31.97% Cu with Wemco-Leeds column and 30.66% Cu with Agitair. Average insoluble 4.699% with Wemco-Leeds column and 6.933% with Agitair. Average recovery 99.464% with Wemco-Leeds Column and 99.54% with Agitair. Selectivity of the Wemco-Leeds Column is superior to the conventional flotation machine without froth washing. Wemco-Leeds columns showed superior performance to conventional cells. Wemco-Leeds column achieved a concentration ratio of 2.009, and Agitair 1.925. The concentration ratio for Mo was 1.958 and for Agitair 1.820. The concentration ratio for insoluble was 0.138 for the Wemco-Leeds column and 0.1448 for Agitair cells. Wemco-Leeds column achieved 35.69% final Cu grade with 96.075% overall recovery, while Agitair conventional cells achieved 34.75% final Cu grade with 96.768% overall recovery. Wemco-Leeds column achieved 1.7365% final Mo grade with 95.322% overall recovery, while Agitair conventional cells achieved 1.5259% final Mo grade with 95.884% overall recovery. Insoluble grade and recovery were also lowered with Wemco-Leeds columns as compared to Agitair conventional cells [39, 57, 121].
Eastern U.S. Coal fields. Eriez-StackCell. Multiple installations of the StackCells technology throughout the U. S. coal industry. Pilot-testing in sulphide applications (Cu-Mo).	3.7 m^3 StackCell was installed as a scalping system ahead of 2 existing flotation columns. Pilot StackCells were installed next to a line of 5 commercial 8.5 m^3 tank cells.	Average recovery increased from 74.4% to 83.7% and combined recovery from 72.5% to 80.7% with StackCells (Mankosa et al., 2018). For the rougher application, each circuit achieved Cu recoveries ranging from 60 to 85%. But the tank cells required approximately a 6-fold longer retention time to achieve the same result as the StackCell. Likewise, comparable recoveries were achieved for the scavenger tests with a 9-fold shorter retention time. 80% Cu recovery was achieved at about 8 min with the conventional system and at 2 min with StackCells [122].
Copper-Molybdenum Concentrator. StackCell pilot-plant testing run in parallel with a conventional mechanical rougher (2 rows) and scavenger (3 rows) cells. Nickel Sulphide Concentrator. StackCell pilot-plant testing run in parallel with a batch of conventional mechanical Denver cells. Ni cleaning application.	Three 0.6 m diameter, d_{80}: 160 μm. 3.0 m in diameter each. d_{80}: 35 μm; feed rate: 500–780 m^3/h pulp. Retention time in inner tank: 2–3 sec. and overall 65–105 sec.	The kinetics of the StackCell were about 2.9 times faster than the lab Denver tests and 6 times faster than conventional mechanical cells. In Cu rougher circuit: Combined Cu grade 14.63% with StackCell at 79.92% cumulative recovery at 1.86 min retention time. Combined Cu grade 15.51% with production rougher at 78.31% cumulative recovery at 11.79 min retention time. The flotation kinetics observed in the StackCells were 2.4 times faster when compared with the lab Denver test and 4.8 times faster than conventional mechanical cells. The kinetics efficiency improvement is due to the reduced "drop-back" during the froth recovery phase, which is reduced because of the reduction in the shear that is present in a conventional mechanical tank cell [123].

During the plant trial period, the Falconbridge Stratcona concentrator had two flotation circuits processing 4.100 t/d each. -74 μm ore was firstly floated in bulk Cu-Ni primary rougher with 25 g/t NaIPX, 14 g/t Dowfroth 250, and pH: 9.2, adjusted with lime. There were three circuits in the concentrator. Cu circuit, Ni circuit, and Po circuit. The main objective was to recover a good bulk Cu-Ni concentrate and leave as much Po behind as possible. Later, the Cu-Ni concentrate was separated into Cu and Ni concentrates by selectively floating Cu minerals, while depressing Ni and iron sulfates with lime at a pH of 12 and a small amount of cyanide. The Cu cleaner circuit produced a final Cu concentrate at 29-30% Cu. The Ni content was then 0.65% without any Po. The primary rougher tails were floated for Ni with little Cu and Po in the secondary circuit at a pH of 9.2. The secondary rougher tails were scavenged for nickeliferrous Po after $CuSO_4$ activation at a pH of 8.2 adjusted by H_2SO_4. The scavenger concentrate was fed to two banks of magnetic separators. The mag-product was reground to 80% -45μm and then floated in the mag-circuit. The non-mag fraction is first thickened and then floated to recover nikelliferrous Po at a pH of 8.2 using NaIPX. The tails were sent to the backfill plant [4].

In order to compare the circuit and column performance at the Stratcona concentrator, Flint and Dobby [124] conducted laboratory-scale column experiments utilizing the non-magnetic circuit feed. They came to the conclusion that the column did not provide any advantages over the traditional cells utilized in the non-magnetic circuit when operating under the current circuit conditions. They claimed that the gangue was naturally hydrophobic (due to the talk presence), incomplete gangue-sulphate liberation (locking), slime coating, and $CuSO_4$ activation in the previous scavenger circuit were the other reasons. Their column tests showed about 30% gangue recovery. Later, Del Villar [115] carried out column flotation tests using a column with a diameter of 5 cm and a height of 10 m to assess the suitability of the flotation column for the non-magnetic circuit. Grade-recovery curves for the column and 5 L mechanical cell were compared. He concluded that in terms of upgrading and Po rejection, laboratory mechanical cells performed better than the flotation column. Since the non-magnetic circuit contained large amounts of easily floating gangue particles. Therefore, it was decided that the Stratcona concentrator was a good candidate for testing the effect of froth washing in the existing mechanical plant cells.

Kaya [4] achieved improved Ni and Cu grades for bank (10 cells) and overall (56 cells) non-magnetic circuit performance with froth washing in the existing plant. At a 0.035 cm/s wash water addition rate, Ni grade increased from 2.6% to 3.7% and recovery from 55% to 68% and Cu grade from 0.7% to 1.4% and recovery from 48% to 66%. Overall circuit performance also increased with froth washing. Overall Ni grade increased from 1.5% to 2.15% and Ni recovery increased from 85% to 87%. at a wash water rate of 0.035 cm/s. Froth washing had a positive impact on both selectivity (Gangue/Ni ratio) and recoveries [5, 12, 41, 62, 112].

Kaya [4] and Kaya and Laplante [12] also conducted froth washing plant tests at Eastmaque Gold Mine Concentrator in Canada. At the Eastmaque plant, historical gold tailings dragged from the Eastmaque lake bottom were ground to about 80% -45 μm, activated with Aero 3477 and 350, and fed to two Maxwell cells, which recover most of the fast-floating Au-bearing pyrite at a high grade. Maxwell cell tails are floated in twelve 14 m^3 Denver cells in rougher and scavenger steps. Rougher and scavenger concentrates are cleaned twice in 2.8 m^3 Denver cells with paddles. Industrial froth washing tests were carried out in the secondary cleaner cells with 25 cm froth thickness in the presence of MIBC as frother. Plant capacity was 650.000 t/y to produce 24.000 oz Au.

Salt tracer (LiCl) tests were performed on the plant cells to determine the wash water split during froth washing. Total water recoveries were 48.5% and 77.7% in the absence and presence of wash water addition. Feed water recovery with wash water was 33% as compared to 77.7% without wash water, which corresponded to a 58% reduction in the feed water recovery. Replacement of feed water containing gangue particles with wash water is the main reason for increasing Au grade in these plant tests [4]. Gangue recovery and classification coefficients (i.e., gangue recovery/water recovery) in the tested second cleaner bank showed a significant reduction in the classification coefficient in all size fractions with wash water addition as compared to no wash water addition. The lower the classification coefficient, the lower the gangue recovery [4]. With froth washing in the existing mechanical flotation cells, the final Au grade increased from 2.3 to 2.7 oz/st with slightly higher recovery (from 66.50% to 67.85%). This 14% grade increase could generate an extra yearly revenue of about a quarter of a million dollars at a very little cost for the current mill operation. The reason for the recovery increase was attributed to the limitation of pyrite surface oxidation at decreased retention times.

Kaya et al. [5] also reported the results of 12 froth washing tests performed at the 2^{th} & 3^{rd} Zn and 3^{rd} and 4^{th} Cu cleaning banks at Les Mines Selbaie, Cu-Zn-Ag sulphate ore, Joutel, Quebec, Canada. A total of 3+3 and 2+1 OK-3 open flow cells were washed to evaluate the bank and plant froth washing amenability. For the Cu circuit, with a 42 L/min wash water flow rate for 3 cells, Cu grade increased from 22.7% to 25.6% and recovery increased from 47% to 51%. For the Zn circuit, with a 95 L/min wash water rate for 6 cells, the final Zn grade increased from 51.6% to 55.3% at a 1% higher recovery. Increasing froth thickness (5-8 cm) in the Zn circuit with froth washing achieved the best Zn metallurgy. Grade increased from 50.9% to 56.1% and recovery from 89% to 90%. A very high wash water flow rate decreased both Cu grade and recovery, and significantly increased Zn grade at the expense of recovery. Since the theoretical maximum grades to be achieved with this type of ore are very close to the reported assays here, it can be assumed that gangue rejection with froth washing is almost complete. Long-term normal plant performance without froth washing was 24.5% Cu and 54.5% Zn grades. During plant trials, the plant was processing ore containing a significant amount of slimy limonite. Even under these hard conditions, froth washing achieved a 1.4% increase in Cu and 1.6% increase in Zn grades [5, 62].

Long-term plant-scale froth washing tests were also performed at the Zinc Corporation of America (ZCA), New York, USA. The plant was processing Zn-Pb sulphate ore. The objectives were to reduce the light element oxides (MgO, CaO, and SiO_2), to increase the final Zn grade, and dilute the pulp phase at the Zn cleaners. After froth washing with spray nozzles, Zn grade increased from 55% to 56.8% at constant recovery, while gangue grade decreased from 6% to 4% during a 45-day froth washing period. Four 2.8 m^3 Denver cells were washed with six spray nozzles per cell. A wash water spray nozzle system was permanently installed, equipped to wash the front part of 9 m^3 cleaner and rougher Denver cells to suppress the voluminous froth [5, 41].

Froth washing tests at the 1^{st}(three 9 m^3 Denver) and 2^{nd} (two 9 m^3 Denver) carbonate cleaner banks were performed at Les Mines Niobec, Quebec, Canada, processing Nb-oxide ores to minimise Nb_2O_3 loss in the concentrate. Froth washing tests were performed for 10 days. The lowest Nb_2O_5 loss in the carbonate concentrate was achieved at wash water flow rates of 150/77 and 159/100 L/min for the 1^{st}/2^{nd} cleaners. Without wash water addition, the Nb_2O_5

loss was 0.25% with wash water addition, 0.165% [41].

7.2 Froth washing in coal flotation

Large amounts of ultra-fines, which were previously thrown away as waste material in the form of ultrafine slurries, are produced during the beneficiation of coals. Because the sulphur in coal ultra-fines causes acid mine drainage to escape into water bodies, ultra-fines disposal has a detrimental effect on the environment. Additionally, the ultra-fines dump footprint takes up space that could be utilized for other purposes. The coal mining businesses lose money as a result of the ultra-fines' loss of combustible value. According to Plessis et al. [63], the recovery of ultra-fines in coal processing can thereby increase profits for the coal processing sector while lowering the environmental impact and enhancing the sustainability of coal mines.

At the beginning, the attempt to apply froth washing in the existing mechanical coal flotation cells was not very successful due to the use of shallow cells, shallower froth thicknesses, self-aeration, and froth paddles. The recovery loss can be attributed to short retention time in the slurry/froth phase, lower particle-bubble attachment, and increased particle detachment due to the froth instability. This implies that wash water can only be used successfully in traditional coal flotation systems with enough extra capacity to counteract the recovery issues brought on by the reduced foam stability and shorter retention period. To create froths that can resist the washing process without collapsing, stronger or staged foaming agents might also be needed [59]. For coal cleaner flotation, Jameson cells and flotation columns have a better grade success due to the entire froth surface washing with wash water in deeper froths. But, few applications have been reported in the coal scavenger cells, which contain the largest amount of gangue particles [21].

McKeon [59] utilised a perforated open-top wash box (30 × 30 × 300 cm) on both sides of the cell in a five 28 m^3industrial Wemco coal flotation with a 44 μm feed size. Wash water boxes were located just behind the froth overflow lip of each cell. Superficial wash water rate was 1.5 gpm/ft^2. In coal flotation, generally, froth paddles were used to remove heavily loaded froth into the concentrate launder. In this study, a wash water box was placed above the froth paddles (Figure 11). Some of the reduced wash water streams were deflected by froth paddles, generating unwashed froth area under paddles (Figure 12). The addition of wash water should not considerably reduce the mean retention time in the pulp phase. If wash water is added from the thickener overflow (clarified makeup water), clays can be coagulated due to the probable coagulant and flocculant remnants in the wash water.

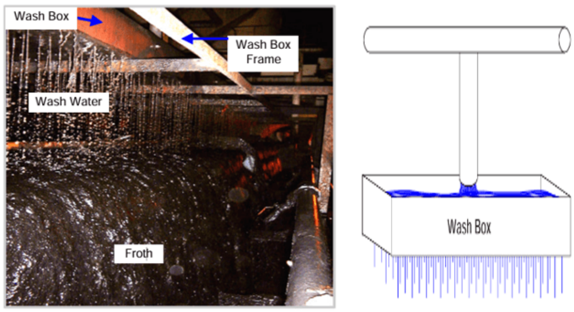

Figure 11 Industrial-scale perforated wash water distribution box for coal flotation in the USA [59]

If the retention time is between 3.5 and 4.0 minutes, froth washing is not a feasible solution for the majority of the coal industry's current flotation circuits. But, it appears to be reasonable for coal flotation banks having excess volumetric capacity and retention time greater than 8 min. before the water is utilised. A very limited effect of froth washing was found for coal mechanical flotation as compared to coal column flotation [59].

According to several industrial froth washing applications reported in the literature, froth washing typically lowers coal yield while improving product quality (by lowering product ash content) [59]. Plessis [120] examined the impact of lip froth washing on coal yield during the flotation of a high ash S. African coal at Anglo American's Goedehoop South (GHS) fine coal plant, which is in contrast to the findings of McKeon [59]. In the plant test trials, the coal yield and coal quality of cells with a lip washing system were compared to baseline cells without lip washing. Lip washing produced yields that were up to 15% greater than baseline cell yields. The ash concentration of the coal product obtained at low (1.30–1.45 kg/t) reagent dosages on lip

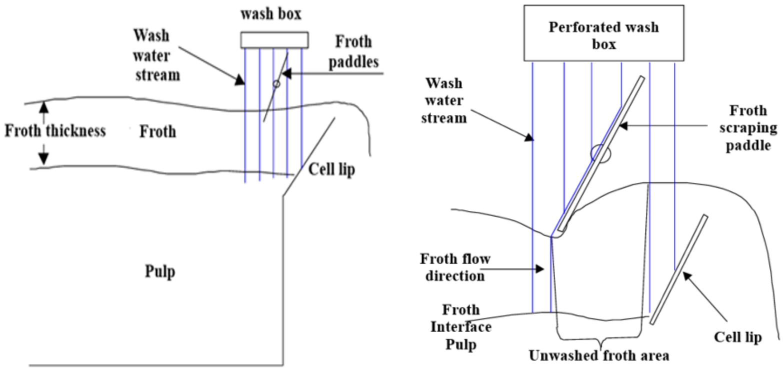

Figure 12 Deflection of wash water by the froth paddle [59]

wash cells was approximately 16.9%, compared to 17.7% with baseline cells. This suggests that higher yields could be obtained at a better quality than those obtained with baseline cells. Coal yields increased but quality decreased on lip wash cells at higher reagent dosages (1.60–1.75 kg/t). Lip washing and baseline flotation yielded coal products with comparable calorific values. For both baseline and lip washing flotation, the yield rose as particle size grew from 75 to 300 μm and then dropped from 300 to 500 μm when different coal particle size fractions were floated independently. With an ideal size class of between 212 and 300 μm, front froth lip cleaning significantly increased the output for finer particles ($<$ 300 μm). Additionally, lip washing of lower-quality coal resulted in a substantially greater output improvement. Following lip washing, the ash level of low-quality coal was likewise similar to that of high-quality coal. To remove hydraulically entrained and entrapped ash particles (gangue) from the froth, Plessis [63] employed lip froth washing, which involves spraying clean water into the froth on the flotation cell's periphery, right inside the froth overflow lip (Figure 13). One of the most important locations for wash water addition is the cell lip, where entrainment is at its worst [4, 53]. In the coal flotation business, froth cleaning has been used on column flotation cells, but there have been few reports of its use on traditional mechanical cells. A few small studies on the use of lip froth washing on fine coal flotation in South Africa were reported by Opperman et al. [125].

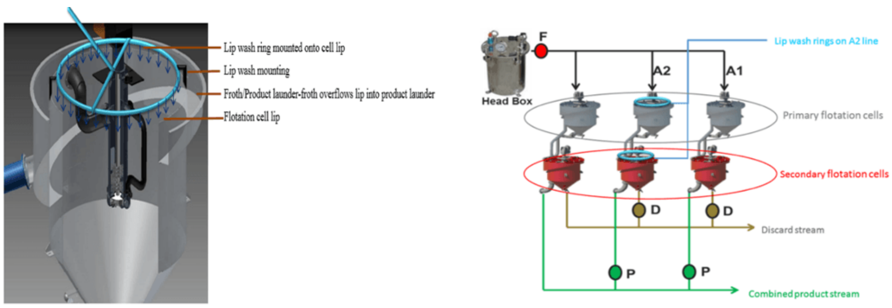

Figure 13 Froth lip washing design for circular dischared dual cells and froth washing trial flowsheet with sampling points in S. Africa (HDPE perforated pipe ring with 16 mm inside diameter; 4 mm holes every 1 cm distance; placed 10 cm above cell lip; 4.5 m^3/h wash water flow rate; even distribution around the cell; fresh water used) [63].

A larger wash-water bias of up to 1.5 may result in a decrease in the recovery of composite/locked particles that are weakly attached to bubbles, according to Young et al. [126]. An enhanced concentration grade results from this. Bhugwandeen [127] tested the impact of bias through scavenger plant experiments. He came to the conclusion that, in contrast to zero bias, a positive bias led to better recovery but a progressive increase in entrainment, and a negative bias resulted in a loss in recovery (the pulp level declined). Particle size, frother dosage, air flow rate, impeller speed, wash water rate, and froth depth are additional factors that have been shown to have an impact on froth recovery [66, 127].

7.3 Wemco-Leeds flotation column cell with froth reflux wash water system

In order to attain a high product grade in comparatively few cleaning stages, the Leeds Column concept uses a series of "barrier" rods, frequently in conjunction with countercurrent reflux water (Figure 14) [57]. A mechanical impeller is included in the lowest part of the Wemco-Leeds flotation column. In order to create a ”bubble-particle” aggregate that rises toward the pulp surface, compressed air delivered to the impeller through a blower is distributed as small air bubbles and combined with the solids. The horizontal rod barriers prevent the aggregate from rising. When the upper and lower rods come into contact, air bubbles form beneath the barrier. When the buoyant air bubble forces are strong enough to overcome the rod's ”hydrostatic pinching” forces, the rods split apart, allowing the air bubbles to keep rising toward the surface. The stripping process will physically remove the lightly held gangue material when the mineral-loaded air bubbles move through the gaps between the sliding rod barriers. By decreasing the entrapped or loosely held material -mostly gangue- attached to the air bubble, this ”stripping” action raises the concentrate's grade.

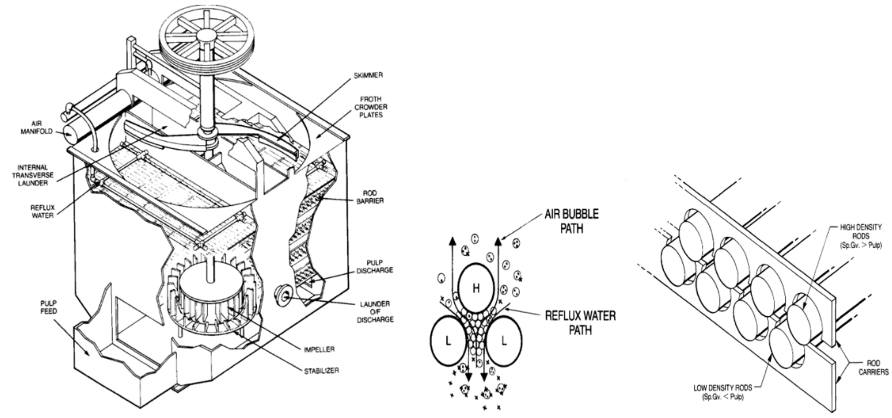

Figure 14 Wemco-Leeds column flotation machine cross-section with reflux wash water addition and rod barrier concept

One on the other, four horizontal barriers are positioned vertically. The pulp in the cell is divided into a number of vertical compartments by this barrier construction. As shown in Figure 14, each barrier is made up of two sets of movable rods in contact. The design of the rod is such that the upper rod has a net buoyant force in the downward direction and the lower rod has a net buoyant force in the upward direction. When the rods are immersed in the pulp, this design produces a hydrostatic pinching force between them. Concentrate grade increased between rod barriers from the lower to the upper sections.

Reflux water, which is wash water, is introduced at the top of the cell by a distribution pipe. It complements the beneficiation activity of the flotation column rod barriers by being dispersed across the pulp surface and leaking downward. It is advisable to evaluate the performance advantages of reflux wash water on an individual basis. Reflux water greatly enhances concentrate grade in various applications, according to experimental testing. However, other examples demonstrated that achieving the needed high-grade product performance did not necessitate the use of reflux wash water.

Wemco-Leeds Column has a low floor space area (i.e., footprint) and a lower height than conventional flotation columns. Wemco-Leeds Column has a rotating impeller and stabiliser mechanism, and perfect mixing and recirculation conditions with reduced pulp short-circuiting. The high particle-bubble mixing intensity creates fast kinetics and high recovery. Wemco-Leeds Column can also use wash water to achieve better metallurgical performance.

Bench-scale Wemco-Leeds Column tests showed significant improvements in ash content over conventional mechanical cell results without froth washing for Eastern U.S. coal. Wemco-Leeds Column approached the maximum achievable flotation performance identified by the release analysis curve. 3.4 m^3 prototype Wemco-Leeds Column was produced (Figure 15).

Rod scaling from calcium carbonate ($CaCO_3$) in the water created a significant operating problem during plant trials and plant applications. Plant experience showed that 1-2 hours of rod barrier steam cleaning plus HCl bath immersion were sufficient to solve this problem. Plant operating experience showed that every 6-month period, rods should be cleaned. Plant trials and experience at the Cyprus-Bagdad Cu plant in the USA showed better metallurgical results for Cu and Mo. First commercial Wemco-Leeds column with reflux water in secondary cleaner duty was implemented at Cyprus-Bagdad. It has been demonstrated that the Wemco-Leeds Column flotation idea works well in ”flotation cleaner” scenarios involving metalliferous ore

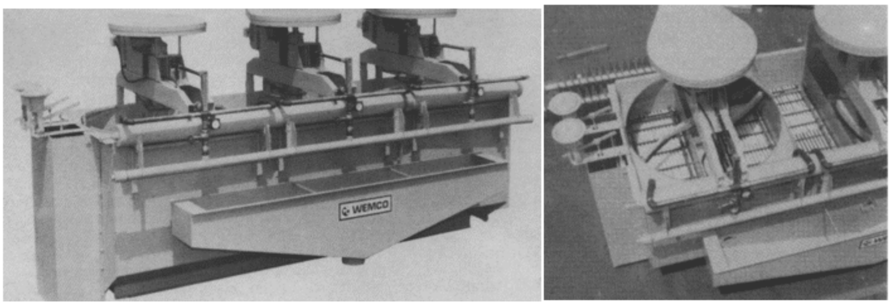

Figure 15 Three-cell R&D Wemco-Leeds Column prototype cross-section and top view (rod barrier assembly and reflux water addition system)

and in fine coal washing applications [39, 57, 121]. According to Degner and Person [57], one important operational parameter was the reflux water rate. But the amount depended on the application. The cleaning flotation of metallic ores required reflux water, whereas coal washing did not.

7.4 Mechanical Eriez StackCell flotation machine with froth washing system

A distinct, high-energy bubble-particle contacting zone (inner tank) dissociated from a larger chamber for froth/pulp phase separation (outer tank) is used by the Eriez StackCell mechanical flotation machine (Figure 16). When compared to traditional flotation machines, this offers a substantially reduced equipment footprint and lighter support loads, resulting in overall savings in capital and installation costs.

StackCell high-rate two-stage flotation machines reduce the flotation volumetric requirement and increase the recovery of fine particles. High specific energy input in the contacting chamber is translated to turbulent kinetic energy through the multi-stage rotor-stator mechanism. With a retention time distribution intended to resemble a plug-flow in a very turbulent mixing environment, the feed moves from the bottom to the top with a short retention period of a few seconds. When compared to conventional flotation machines, this obtains turbulent dissipation rates that are roughly four to five times higher. Except for a space between the side walls and a revolving cover on the top of the vessel, the internal tank is hydraulically isolated from the main tank on all sides. Based on a slight positive pressure between the tanks, aerated pulp is forced through the annular gap between the internal tank wall and the spinning lid. The internal tank's bubble-particle collection is made possible by this arrangement. Because of the tanks' good isolation, the second outer tank can be used without disturbance and only serves to separate the aggregates of bubble particles into a froth phase that is recovered in a laundry. The efficient use of wash water is also made possible by the absence of mixing in the outer tank. By producing deep froth to enable froth washing, which can be utilized to reject hydraulically entrained gangue in the concentrate, flotation selectivity is enhanced [122].

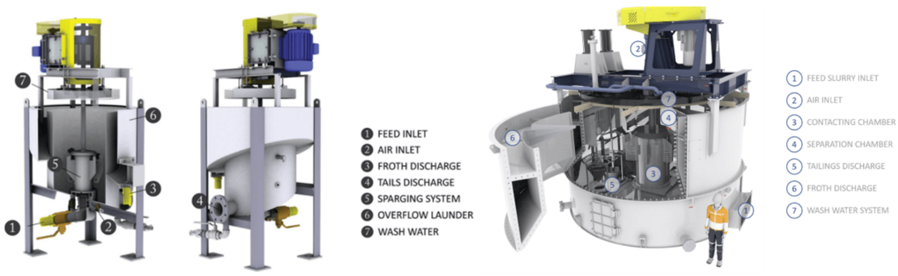

Figure 16 Pilot and Industrial scale Eriez StackCell mechanical flotation machine cutaway

By raising the flotation kinetic rate constant of materials, StackCell flotation reduces the retention time needed by 75% to 85%. selective recovery of slow-floating minerals and fine particles, which boosts mining projects' profitability and environmental sustainability. Wash water is used to reject entrained small particles from concentrate froth, increasing flotation selectivity. The StackCell offers lower flotation circuit size and power consumption while providing improved mineral recovery and concentrate grades for mining firms looking to minimize the environmental effects of flotation circuits and maximize profitability. Mankosa et al. [122] reported that 80% Cu recovery was achieved at 8 min. in laboratory conventional flotation tests, while StackCell achieved the same recovery in 2 min. only. SC-200 is a 65 m^3 tank with 300 m^3 equivalent conventional flotation capacity. SC*200 cells achieved energy savings of 60% [122]. It seems that Eriez StackCells achieves both faster kinetics with a high-shear aeration chamber and higher grade and/or recovery with froth washing in deep froths. The StackCell was designed to provide extremely focused energy input per unit volume of feed. Energy density of the StackCell (250 kW-min/m^3) exceeds both lab-scale conventional flotation cell (210 kW-min/m^3) and column flotation (100 kW-min/m^3) at normalised Cu recoveries of 64%, 48%, and 36%, respectively [122].

After pilot-scale trials, StackCell technology was installed in the Eastern USA coal field industries on a full scale. Pilot-scale testing in Cu-Mo sulphide applications also showed positive results for the StackCells application in the USA and Western Australia [122, 128].

Eriez's StackCell is a relatively novel froth flotation device designed to reject fine gangue particles and recover valuable fines/slimes. It was created in response to the technical and design issues that are frequently connected to current conventional flotation technology, such as Jameson cells, mechanical cells, and self-aerating cells. High energy usage, a big floor area, and cell size were some of these difficulties. In addition to offering an effective separation, this two-stage flotation method was specifically created to address the aforementioned issues with regard to equipment size, energy consumption, and installed costs [128].

At the Mount Keith Nickel Concentrator in Western Australia, pilot-scale StackCell test work was completed to measure the technology's benefits while serving as a cleaner scavenger, rougher scavenger, and cleaner scalper. In a tougher scavenger role, a single StackCell unit was able to recover up to 16.8% Ni at grades appropriate for that circuit. 16.5% Ni recovery was possible when performing a cleaner scavenger job, albeit at a somewhat lower grade than the cleaner circuit. A final quality concentration with a maximum Ni recovery of 59.5% for the single-stage StackCell was produced by further testing of the StackCell in a cleaner scalper role. Given that they were accomplished with contact times of 55 and 93 seconds, respectively, these one-stage recoveries are quite remarkable. Concurrent with these tests, laboratory-scale experiments revealed that the StackCell could recover up to half as much as a traditional flotation cell with a 16-minute retention time. The flotation kinetics have significantly improved as a result. A lab-scale on/off trial that replicated the downstream cleaner recleaner block performance was used to determine the overall impact of using a StackCell in the midst of the process. According to this analysis, this circuit block has an overall net advantage of 0.7% to 2.0%. An industrial-scale installation was being investigated since this represents an economically important Ni metal yield [128]. The use of StackCells in Mt Keith Ni concentrator significantly increased the fine (-15 μm) valuable particle recovery via a high-energy bubble-particle contacting zone and decreased gangue entrainment via froth washing in a larger chamber for froth/pulp phase separation.

Wasmund et al. [123] reported that the two-stage flotation by StackCell provided accelerated flotation kinetics with both 0.6 and 3.0 m diameter cells in the Cu-Mo and Ni sulphide rougher and cleaner plant tests (Figure 17). They suggested that the Denver laboratory test is a useful scale-up method for industrial StackCells, but a scale-up factor of 0.3 to 0.4 is more appropriate, compared with 2.0-2.5 for conventional mechanical cells. Therefore, StackCells can reduce the required cell volume 5 to 6 times than conventional flotation cells (https://www.eriez.com/Documents/Literature/ Brochures/Products/ Flotation/StackCell/Wasmund-et-al-Copper-2019-StackCell.pdf).

Figure 17 0.6 m diameter Stackcell used in pilot trial study for Cu-Ni concentrator

Eriez are producing SC20, SC-50, SC-70, SC-100, and SC-200 StackCells. Some operating StackCells were implemented in Australia, S. America, and N. America and showed excellence in a range of operations (https://www.eriez.com/Americas/Products/Flotation/StackCell-Flotation.htm# Product_Features).

8 The role of wash water in froth cleaning

Five ways froth washing in mechanical cells can affect metallurgical performance. First, wash water improves water drainage between bubbles and removes fine gangue particles that are mechanically and hydraulically stuck. The thickness of the inter-bubble water film, the rate of water drainage, and the probability of reattachment of hydrophobic valuable particles play an important role in the froth phase. The thicker the inter-bubble water film, the larger the amount of water draining from the froth phase and the more effective the secondary concentration. Second wash water breaks the bubble on the top of the froth layer, causing it to pour their load on the bubbles below. A crowding effect is produced in which mineral particles compete for places on the reduced bubble surfaces, creating a heavily loaded clean froth. The third, wash water stabilises the froth by compensating for water loss and reducing coalescence. With wash water, bubbles remain spherical and further apart from each other. Wash water can also prevent overloading, which inhibits drainage, by lightening the froth and allowing the concentrate to be pulled harder. Fourth, washing water slightly decreases particle retention time in the froth phase. Fifth, wash water decreases the overall feed water recovery into the concentrate by displacing it. Concentrate grade increases largely due to the increased rejection of the entrained/entrapped or weakly attached gangue particles. Recovery increase is mainly related to the increased froth stability with wash water [62, 112].

9 Wash water addition type

The froth washing process involves a counter-current water spraying onto/into the froth by perforated pipes, spray heads, wash boxes, etc. The wash water reduces bubble coalescence and stabilises froth. The additional water aids in the drainage of entrained/loosely held particles back into the pulp phase by dislodging the entrained liquid that transports gangue particles. Wash water reduces retention time in the cell by increasing the flow through the cells. Adding wash water increases total throughput. Wash water demand can be reduced by using deeper froths with additional drainage capacity. Froth thickness in mechanical cells can be increased by adding froth weirs without decreasing pulp retention time [59]. Wash water should be distributed evenly across the entire froth surface. As froth moves to the lip and into the launder, this gives it more time to drain. The wash water does not have enough time to properly drain and eliminate the gangue particles when the froth is shallow and flows quickly. Rather, the froth water is simply diluted, and the result is used to short-circuit or sweep hydrophilic particles over the cell lip. Increased natural froth drain-back from deep, slow-moving froths improves the separation of froth from entrained water and lowers water carryover. Combining a deep froth with wash water improves the decrease of hydraulic entrained gangue (Figure 18).

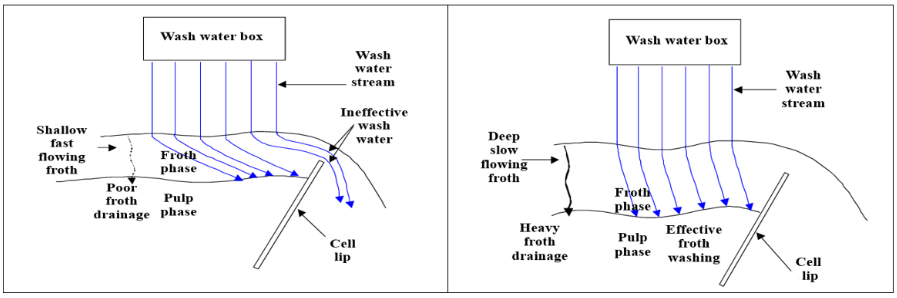

Figure 18 Ineffective froth washing in shallow froths, b) Effective froth washing in deep froths [59]

Wash water should be added as gently as possible, like drops/sprays, without bursting the froth. Forceful water jets increase bubble coalescence and may decrease valuable recovery. Preferably, in single-sided overflow cells, wash water should be added above the froth and over the entire cell through perforated pipes, spray nozzles not only to the cell lip [4].

Well optimised froth washing in flotation increases concentrate grade, flotation recovery, froth stability, and mobility, and thus enhances the overall performance in the cell [4, 5, 41] in a single-stage flotation. Despite the success achieved with froth washing both in mechanical and pneumatic flotation machines, especially in flotation columns and the Jameson cells (particularly in the coal flotation plants), some factors lead to suboptimal performance if they are not optimised very well. These operating parameters include wash-water flow rate, water quality/content, wash-water distribution system type and mechanism, and washed froth surface. Optimisation of these parameters was critical for metallurgical performance. A flotation cell's metallurgical performance may be compromised by wash water maldistribution, which also influences the degree of froth mixing, channelling, and short circuiting in the froth. Froth washing has been utilized to combat further entrainment caused by an excess of small particles in the pulp [21]. Froth washing is generally applied in existing front-side overflowing mechanical flotation cells by washing at the lip. But, the entire froth surface of mechanical cells can be homogenously washed by wash water for the two-sided overflow rectangular or whole peripheral surface overflow cylindrical mechanical cells [4]. The entire froth surface of flotation columns and Jameson cells is washed by wash water on an industrial scale. Froth washing cleans water in the froth and displaces loosely attached gangue effectively [21]. Froth washing is also very effective in mechanical flotation cells, where froth thickness (5-30 cm) is significantly less than column flotation (50-100 cm). Froth permeability is enough for downward wash-water flow. For heavily loaded froths, like in coal flotation, froth weir addition can be used to increase froth thickness in mechanical cells without the loss of pulp retention time.

Kaya [4] used a wash water rate of only 7% to 12% of the feed water. Wash water with the same frother concentration as in the flotation cell feed should be added to the fresh wash water to stabilise the froth [5,64,65]. At the low wash water rates, concentrate recovery increased than without wash water addition, due to the better froth stability. At the medium wash water addition rates, both concentrate grade and recovery increased. At the highest wash water addition rates, more gangue is entrained as compared to the medium wash water addition rates. Wash water should be added preferably over the entire froth surface, if it is possible. Wash water can be added above, in, and under the froth phase without disturbing froth stability [5]. Wash water should be added evenly, steadily, and gently to the froth surface like rain or spray. Wash water distribution system alloys froth to be rinsed just before discharging from the cell lip. If there is a scraper mechanism, the wash water system can be placed before the scraper towards the cell back.

Froth washing also affects both froth rheology and stability. Froth becomes less viscous with wash water [20]. Froth stability and froth mobility properties have a direct impact on both froth and flotation performances. Wash water addition influences froth stability and mobility. Kaya [4] reported that wash water addition reduced bubble coalescence, which led to improved flotation recovery. In addition, with the addition of wash water, the bubble lamella thickened, and a high drainage rate effectively reduced gangue entrainment by washing, and the number of large hydrophobic particles held in the froth increased. This secondary concentration in the froth phase increased both grade and recovery. As the froth builds up and expands due to bubble coalescence, hydrophilic gangue particles drop back and water drains through Pleatau borders, which leaves the upper layers of the froth dry. Wash water addition replaces the water lost in the upper layers of the froth, thus increasing froth stability by eliminating the dry froth upper layer [4, 66]. A reduction of the loss of particles in the froth can be achieved by decreasing coalescence and bubble-bursting events.

In rougher flotation circuits, where the concentrate flow rate is low, a low positive bias is suggested for good froth washing and better metallurgical performance. However, in a cleaning circuit, where the mass flow of concentrate is high, a significantly higher wash water flow rate will be needed to substitute the water being carried over in the concentrate [21].

10 Limitations of froth washing

Wash water has two drawbacks. Firstly, gangue rejection is partial. Froth washing significantly enhanced the tail flow rate at Eastmaque Gold Mine and substituted wash water for feed water in the concentrate. This led to a notable decrease in entrainment. Reducing entainment by half, as seen in the majority of laboratory and pilot-scale testing, may be a more reasonable expectation. The second restriction is the reduction in retention time brought on by dilution (a comparable issue with flotation columns). The Stratcona mill, which demonstrated lower recoveries with high wash water rates, is a prime example of this. Au recovery decreased in the second cleaner with wash water at Eastmaque due to the flotation circuit's excess capacity. Nevertheless, the first cleaners eventually found the misplaced Au. As a result, there was no discernible loss of recovery; instead, overall Au recovery rose with wash water [4].

11 Froth washing types, delivery mechanisms, and washed area

The design, position, and operating conditions of the wash water distributor are important and critical for better metallurgical performance [5, 62, 65]. Wash water can be added on the froth (surface washing), within the froth (internally), or at the pulp-froth interface. Inserting/plunging the wash water distributor inside the froth may cause plugging/blocking. Frequent cleaning of the plugged distributor is a problem. Internal froth washing produces drier and surface washing generates wetter froths. Dryer froths lower the loss in mineral recovery compared to the surface washing and achieve better recoveries. Plunged horizontal (T-shaped) and vertical nozzle/ injectors were also tested by Ireland et al. [129]. Surface washing creates additional froth expansion and is maintenance-free. Problems are easily detected and corrected. The addition of wash water at the interface or under froth aims to wash unattached gangue particles in the wakes of the upward-moving bubbles without entering the froth phase. Under froth washing was patented by Dobby and Cosick [67].

In industrial plant-scale froth washing, perforated PVC pipe or spray nozzle types of wash water distributors can be mostly used for the entire froth surface or overflow lip wash (Figure 19). The manifold system provides water to the nozzles, and they spread horizontal jets of wash water uniformly to the froth surface. Nozzles can be angled, disc-type, chamber-type, or flat-type [65]. Horizontal straight parallel or cylindrical perforated pipes/tubes shower the froth surface uniformly. Pipes are spiralled and suspended through a manifold above the froth in cylindrical cells. On one side, overflowing cells, showers spray water on 40% of the froth surface, and perforated pipes 70% of the froth surface. Perforated wash water boxes/trays were also used in coal flotation in the USA [59]. Rectangular drip pans have holes at the bottom and open at the top. Wash water boxes cover the entire cell lip and are mounted on the racks. These boxes can not be immersed in the froth. Clean Process Technologies developed uniquely designed trays to provide an evenly distributed flow of wash water to the flotation cell froth layer. Removal of slimes and clays, removal of entrained materials, and increased mobility are claimed with froth washing. Slimes and clay removals can reduce coal product ash and also aid dewatering. Removal of entrained material can reduce coal product ash by removing product contaminants. Also addition of wash water can increase froth mobility (https://www.cleanprotech.com.au/PDF/CleanProTech_Flotation_FrothWashing_System.pdf).

Figure 19 Perforated pipe, wash water tray, and spray nozzle type froth washing distributors

In froth washing, fresh water usage is important. If recycled water with solids in it is used, plugging in the distributor pipes or even trays may occur in coal flotation (Figure 20). Wash water rings are notoriously hard to clean and remove these blockages once they occur. Both of these circumstances will reduce the effectiveness of the froth washing water, resulting in a higher ash product, lower froth mobility, and reduced yield (https://www.cleanprotech.com.au/PDF/CleanProTech_Flotation_Froth_Washing_System.pdf).

Table 4 summarises and compares the advantages and disadvantages of the suggested industrial froth washing technologies on, in, and under the froth phase. The best froth washing system for each circuit should be tested and optimised in plant tests by experts on the subject. It seems that the entire froth surface washing is better than cell lip washing for highly-loaded and/or less-loaded ores.

Generally, froth washing reduces gangue entrainment, therefore enhancing metallurgical performance. Single-stage froth washing can be adequate for roughing+cleaning stages. Froth washing reduces bubble coalescence, increases drainage, and improves froth stability. For some persistent and deep froths (like coal), there will be no need for froth skimmers/paddles for overflow to the launder. There is also no need for skimmer and froth crowder plates for many metalliferous ore beneficiations with froth washing.

Figure 20 Plugged/blocked the wash water tray and wash water distributor ring pipes due to the poor quality of clarified coal water

Table 4 Comparison of the advantages and drawbacks of different froth washing technologies in a plant-scale

Suggested Froth Washing Method	Advantages	Disadvantages
Froth washing above the froth phase (surface washing) by perforated pipes, showers, nozzles, and boxes/trays (1) Entire froth surface washing (2)Cell lip washing	Monitoring and maintaining plugging/ blockages are easy and online. Plugging/blockage possibilities are low, the system is self-cleaning and maintenance-free. Froth expands, and froth retention time increases slightly. Perforated pipes and boxes can be produced homemade. Nozzles are not very expensive, Design, construction and application are easy and cheap. Application is common Both concentrate grade and/or recovery can be increased. Most suitable for highly-loaded froths (coal) Saves water, Effective for reducing gangue at the cell lip, which increases the concentrate grade Application is common Most suitable for less-loaded froths (low-grade sulphide ores)	Some wash water is directly short-circuited to the concentrate. Maldistribution should be inspected by cameras, Washing water trays sometimes may prevent froth overflow, Froth mixing should not be high, Nozzles/injectors are expensive than pipes and trays. Short-circuiting of some wash water to the concentrate when poorly monitored
Froth washing in the froth phase (submerged pipes or nozzles)	Yield dry concentrate, Lower reduction in mineral recovery, Produce a higher grade concentrate, Gives a higher grade concentrate Application is common	High possibility for distributor plugging/ blocking, Requires frequent maintenance and cleaning to prevent water maldistribution.
Froth washing under pulp-froth interface (perforated pipes)	Minimises bubble breakage and froth drop-back, which improves both grade and recovery compared to surface and inner washing.	Installation is difficult and requires more pipes, Difficult to monitor and clean for plugging/ blockage. Application is scarce

In the existing flotation plants, froth washing tests should be carried out by experts for each circuit's optimisation. The optimum wash water rate and washing system should be determined; otherwise, froth mixing may lead to low recovery. Froth washing is more difficult for highly loaded and persistent froths (like coal flotation) and containing hydrophobic gangue (like graphite) as compared to the low-grade metallic sulphide ores. Bias control is important for metallurgical performance. Soft and fresh water usage can prevent plugging of the distributors. Plugging, blocking and/or scaling the wash water distributor system results in improper froth washing.

12 The use of wash water in plant circuits

Froth washing in mechanical cells achieves three functions in mechanical cells: froth cleaning (secondary concentration), pulp dilution, and froth knock-down for voluminous froths. Froth washing is best suited for the later stages of separation (i.e., cleaners or recleaners). If excess capacities are available, there is no restriction to use froth washing in rougher (like in ZCA). If tailing of the washed bank refloated (closed-circuit), better metallurgical performances can be achieved than open-circuit operation (like in Eastmaque). In most plants, dilution water is added into the concentrate launders, junction boxes, or conditioning tanks. Froth washing both cleans the froth and dilutes the pulp. Therefore, water addition to launders, boxes, or tanks can be minimised with wash water addition. The use of perforated pipe type distributors over the froth phase for watery froths is suggested over spray nozzles, as they minimise water requirement and homogeneously distribute water without plugging.

Placing a wash water distribution system near the overflow weir, where entrainment is most severe and requires minimum maintenance, can be used for lightly-loaded bubbles and on the entire froth surface for heavily-loaded froths. For highly-loaded mineralised and polygonal froths, which are voluminous and persistent (also contain more gangue), wash water spraying the entire froth surface should be advised [62, 112]

13 Flotation cells with built-in froth washing systems

Today, all industrial-scale Jameson cells, all flotation columns, Wemco-Leeds Column Cells, and Eriez Stack Cells have built-in froth washing systems.

14 Conclusions and suggestions

Gangue recovery mechanisms, entrainment, entrapment, and slime coating, closely follow water recovery. At finer particle size distributions, gangue recovery is more severe. The water recovery in the froth is significantly influenced by pulp density, air flow rate, and mixing speed. The froth stability is altered by the collector and frother. Because of increased gangue mineral entrainment, superior froth stability is somewhat unfavourable to flotation. Generally, a reduction in coalescence and bursting increases froth stability and also improves concentrate recovery. Decrease in froth retention time and increased froth mobility may reduce some froth drainage and may reduce the recovery (like in highly loaded coal flotation). The hydrophilic gangue particles are flushed back into the pulp by a downward counter-flow to the entrained feed liquid. This increases the froth product's grade.

Wash water addition in flotation cells may increase both concentrate grade and/or recovery without the need for several cleaning stages. Wash water use in mechanical cells can offer several metallurgical and economic (i.e., reduced transportation and smelting costs) benefits for some existing and new plants. Water amount and its quality are important for froth washing. Froth washing at the cell lip may minimise water consumption. Only clean and fresh water should be recommended to add as wash water. Plant recycled water, seawater, treated sewage water may contain residual solids and contaminants that affect flotation or block the water distributor system. Tracer or conductivity techniques to monitor froth washing efficiency or to select the optimum operating conditions can be used in plant-scale implementations.

It is proven in many industrial tests that froth washing in mechanical flotation can be more beneficial for single-stage flotation, thin froth flotation, fine feed, or low-grade ores/tailings reclamation. The froth washing in plant-scale mechanical flotation cells can be economically and metallurgically attractive, simple, and most importantly, inexpensive to test and implement for many existing flotation plants. Cleaners and recleaners can be the best circuits for froth washing. Testing for froth washing in the existing cleaning circuits of plants may achieve comparable results by implementing column flotation and/or pneumatic flotation cells/columns. Eriez StackCell and Wemco-Leeds cells are using wash water addition.

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Muammer Kaya: Writing- visualization, investigation, classification, and reviewing.

Conflicts of interest

The author declares that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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